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IMPACT OF AIR POLLUTION ON VEGETATION NEAR THE COLUMBIA GENERATING STATION

Wisconsin Power Plant Impact Study

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The impact of air pollution from the coal-fired Columbia Generating Station upon vegetation was investigated. Air monitoring of O_3 and O_2 documented levels that occurred before and with operation of the generating station. Field sampling of alfalfa, lichens, and white pines was undertaken before and after initiation of generating station operations.

Controlled environmental exposures were undertaken with separate cultivars of crop species grown in the vicinity of the generating station. Alfalfa, carrots, mint, peas, beans, and trembling aspen were exposed to SO_2 and O_3 to establish minimum threshold pollutant levels for injury from these pollutants. None of the species were found to have threshold levels below the concentrations of SO_2 recorded around the generating station and only trembling aspen was found to have a threshold level for injury that was less than the concentrations of O_3 recorded around the generating station. All species were found to be injured by lower concentrations of SO_2 in combination with O_3 than with SO_2 or O_3 exposures alone. Only trembling aspen was injured by a combination of SO_2 plus O_3 that was less than the levels of these combined pollutants monitored around the generating station. Injury symptom development is described and illustrated for SO_2 and O_3 upon the separate plant species.

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FOREWORD

The U.S. Environmental Protection Agency (EPA) was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Polluted air, water, and land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated attack on the problem.

Research and development, the necessary first steps, involve definition of the problem, measurements of its impact, and the search for solution. The EPA, in addition to its own laboratory and field studies, supports environmental research projects at other institutions. These projects are designed to assess and predict the effects of pollutants on ecosystems.

One such project, which the EPA is supporting through its Environmental Research Laboratories in Duluth, Minnesota, and Corvallis, Oregon is the study "The Impacts of Coal-Fired Power Plants on the Environment." This interdisciplinary study, involving investigators and experiments from many academic departments at the University of Wisconsin, is being carried out by the Environmental Monitoring and Data Acquisition Group of the Institute for Environmental Studies at the University of Wisconsin-Madison. Several utilities and state agencies are cooperating in the study: Wisconsin Power and Light Company, Madison Gas and Electric Company, Wisconsin Public Service Corporation, Wisconsin Public Service Commission, and Wisconsin Department of Natural Resources.

During the next year reports from this study will be published as a series within the EPA Ecological Research Series. These reports will include topics related to chemical constituents, chemical transport mechanisms, biological effects, social and economic effects, and integration and synthesis.

This report presents the details of a study to determine the impact of air pollutants from a power plant on vegetation in the area surrounding the plant.

Norbert A. Jaworski
Director
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ABSTRACT

The impact of air pollution from the coal-fired Columbia Generating Station upon vegetation was investigated. This station, generating a maximum of 1050 MW and located in south central Wisconsin, began operations in 1975.

Air monitoring of ozone (O_3) and sulfur dioxide (SO_2) documented levels that occurred both before and with operation of the generating station. Sulfur dioxide emissions from the generating station produced an average of two fumigations at ground level each month at concentrations between 100 and 250 $\mu g/m^3$ for 2- to 3-h periods. A maximum of 389 $\mu g/m^3$ SO_2 for 1 h was recorded at one station. Nitrogen dioxide (NO_2) emissions (monitored only after initiation of generating station operations) produced fumigations at concentrations between only 60 to 80 $\mu g/m^3$ for 2- to 3-h periods at ground level. A maximum of 101 $\mu g/m^3$ NO_2 for 1 h was recorded. Ozone levels present in the ambient air of the area were occasionally elevated to concentrations of 140 to 180 $\mu g/m^3$. A maximum of 311 $\mu g/m^3$ O_3 was recorded with clear skies and southerly winds.

Field sampling of alfalfa, lichens, and white pines was undertaken both before and after initiation of generating station operations.

Alfalfa had no evidence of visible injury from air pollutants and there was no change in yield of harvestable forage at the 16 sites sampled in the years since operation of the station began. All alfalfa tissue samples collected in 1978 had significantly more sulfur (S) than samples taken in 1974. The increase was within the optimum range of S content for alfalfa tissue and within the range of normal annual variation in S uptake from soil.

A small percentage of white pine trees had injury to needles from air pollutants at all 15 sites sampled in all years before and after operation of the generating station. There was no increase in injury with operation of the generating station. The percentage of trees injured varied from 1 to 4% in separate years.

Sampling of lichens on oak trees at 29 sites surrounding the generating station indicated that the number of species present and the total number of observations of all species did not decrease in a 1978 sampling compared to a 1974 sampling. A few species were found to have statistically significant changes in distribution between the 2 yr but these changes were of questionable importance because the species occurred on < 10% of the trees sampled.

Open-top field chambers, utilized in 1976, did not indicate that ambient pollution levels had a measurable influence upon alfalfa growth or yield, however, yield variations in the field plot were large and limited the significance of comparisons. Detailed study of the environment of open-top field chambers demonstrated that the radiation level and evaporation within chambers was not the same as in open areas.

Controlled environment exposures were undertaken with separate cultivars of crop species grown in the vicinity of the generating station. Alfalfa (*Medicago sativa* L.), carrots (*Daucus carota* L.), mint (*Mentha piperita* L. and *M. spicata* L.), peas (*Pisum sativum* L.), beans (*Phaseolus vulgaris* L.), and trembling aspen (*Populus tremuloides* Mich.) were exposed to SO_2 and O_3 for 1 to 8 h to establish minimum threshold pollutant levels for injury from these pollutants. None of the species were found to have threshold levels below the concentrations of SO_2 recorded around the generating station and only trembling aspen was found to have a threshold level for injury that was less than the concentrations of O_3 recorded around the generating station. All species were found to be injured by lower concentrations of SO_2 in combination with O_3 than with SO_2 or O_3 exposures alone. Again, only trembling aspen was injured by a combination of SO_2 plus O_3 that was less than the levels of these combined pollutants monitored around the generating station. Injury symptom development is described and illustrated for SO_2 and O_3 upon the separate plant species.

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SECTION 1

INTRODUCTION

This report details research undertaken to document changes in the incidence of air-pollution injury to terrestrial vegetation before and after the initiation of operations of the Columbia Generating Station near Portage, Wis. Baseline data were collected prior to the start of station operations, from 1971 to March 1975, and studies have continued during operation of the station, from March 1975 through 1978. Research was conducted in three major areas. First, ambient air was monitored near the generating station to document the concentrations of air pollutants emitted by the station itself (nitrogen oxides (NO_x) and sulfur dioxide (SO_2)) and air pollutants present in the ambient air (ozone (O_3), NO_x, and SO_2)) This research is reported in section 3. Second, several plant species known to be sensitive bioindicators of the presence of SO_2 were sampled in the field. The primary species sampled regularly were alfalfa (*Medicago sativa* L.), eastern white pine (*Pinus strobus* L.), and lichen species on black oaks. In addition, two other sensitive native species, blackberry (*Rubus* sp.) and giant ragweed (*Ambrosia trifida* L.), were observed in conjunction with alfalfa sampling. This research is reported in sections 4, 5, and 6. Third, in controlled laboratory settings selected plant species were exposed to SO_2 and O_3 to determine minimum threshold sensitivity levels and to obtain dosage-response information on the plant species. The plant species included five crops commonly grown in the generating station area: peas (*Pisum sativum* L.), carrots (*Daucus carota* L.), mint (*Mentha piperita* L.), beans (*Phaseolus vulgaris* L.), and alfalfa (*Medicago sativa* L.); and one tree species, trembling aspen (*Populus tremuloides* Mich.). The sensitivity of eastern white pine to laboratory exposure to pollutants had been evaluated in previous studies (Houston 1974). Exposures to pollutants in the laboratory are reported in sections 8 and 9.

The Columbia Generating Station is a facility consisting of two 527 MW units, one placed in operation in March 1975 and the second at the ending period of this report, in June 1978. The first unit has a 158 m (500 ft) high stack and the second unit a 198 m (650 ft) high stack. Particulates are controlled by electrostatic precipitators but there is no stack control of SO_2 emmissions. The station has averaged 350 M Watts of electricity over the period of March 1975 through June of 1978. The station utilizes low sulfur coal from Coal Strip, Montana that has an average of 0.8% S. The average amount of coal burned has been 4,600 tons/day over the same period.

The station is located on the narrow flood plain of the Wisconsin River in south-central Wisconsin, 40 km north of Madison. There are no other major sources of air pollution within a 120 km radius of the site except for the Madison metropolitan area with a population of 225,000.

The area within a 16-km radius of the generating station consists primarily of slightly rolling farmland with elevations no more than 60 m above the level of the station. The major exception is a high ridge west of the station. This ridge begins 8 km west of the station, across the Wisconsin River, rises 200 to 250 m above the elevation of the station, and extends in a westerly direction for more than 16 km. South of the generating station, soils are primarily well-drained, deep silt loams. North of the station soils are primarily loamy sands and sand interspersed with low marshy areas and small lakes.

Present vegetation in the area is a mixture of agricultural cropland, pasture, tree plantations, marshland, and native woodland. The generating station is in the prairie-forest border region of Wisconsin (Curtis 1959), where the native vegetation consists of a mixture of prairie, oak opening, and predominantly oak woods in the uplands, oak and maple woods in the lowlands, and tamaracks or marsh grasses in poorly drained areas. Because of higher elevations and more acid soils in the hills to the west of the generating station, native vegetation there includes many northern hardwood forest species.

Agricultural land predominates in the area. To the south of the generating station, in the areas with deep, silt loam soils, high value grains and dairy-farm crops are grown. North of the generating station the sandy soils are used for marginal grain and dairy-farm crops. Interspersed with these are a few farms with organic soils planted to high value vegetables. West and north of the station tree plantations are found, but a greater proportion of the land is in native forest (usually second-growth) than in the land to the south and east. Field corn, oats, alfalfa, and sweet corn are the most widely grown crops (Table 1, Table 2). Review of literature on sensitivity of locally grown crops indicates that all crops except corn and tobacco are sensitive to SO_2, while tobacco, oats and potatoes may be the most sensitive to oxidants. Alfalfa, field corn, oats, soybeans, and wheat are associated with dairy-farm operations and have the largest acreages in areas with silt-loam soils. Sweet corn and peas for canning are grown primarily in the southern and eastern parts of the area. Additional crops, including red clover, bromegrass, tobacco, barley, and rye cover small acreages and are grown on scattered farms throughout the area.

On the drained marshes and sandy areas north of the station, several vegetable crops are grown. Although relatively few acres are cultivated, the value of these crops is high and crop injury would be economically significant. These crops include potatoes, snap beans, cucumbers, and peppers grown on sandy soils with overhead irrigation; and lettuce, onions, carrots, mint, and potatoes grown on organic soils in drained marshes.

The largest economic loss would result from general injury to a widely grown, susceptible crop such as alfalfa. Injury to a lesser crop may result in great economic loss when the value of the crop is high and the injury results in a large reduction in harvestable yield.

The field-sampling program reported here has included bioindicator species representing a wide variety of growth habits and susceptibility

TABLE 1. EXISTING LAND USE IN COLUMBIA COUNTY SURROUNDING THE COLUMBIA GENERATING STATION*

Land type	Area ha	Area %
Crop land	101,000	48.8
Pastures	11,000	5.3
Woodlands	45,000	21.7
Wetlands	13,000	6.3
Right-of-ways	6,000	2.9
Residential, industrial, recreational and agricultural	22,000	10.6
Water	9,000	4.4
TOTAL	207,000	100.0

*Adapted from: U.S. Dept. of Commerce. 1974. Agricultural Census: Wisconsin. Vol. 1, Part 49, U.S. Dept. of Commerce, Washington, D.C. 1977; from Wisconsin Forest Inventory by the Forest Management Division of the Wisconsin Conservation Department, 1959; and from Columbia County Planning Department Report, Columbia County, Wisconsin, 1970.

TABLE 2. MAIN CROPS GROWN IN COLUMBIA COUNTY IN 1978*

Crop	Area, ha
Field corn	60,750
Alfalfa hay	20,050
All other hay†	2,025
Oats	7,490
Soybeans	2,635
Wheat	1,055
Canning peas	4,170
Sweet corn	4,900
Potatoes	205
Tobacco	155

*Adapted from Wisconsin Department of Agriculture Statistical Reporting Service Crop Report for 1978.

†Primarily red clover and bromegrass.

patterns. These species or groups of plants--alfalfa, white pines, and lichens--have been shown in previous literature to be sensitive to SO_2. Data on distribution, evidence of pollution injury, and productivity of these plants were collected for this report before and after the Columbia Generating Station began operation in March 1975.

Alfalfa is an introduced herbaceous crop plant that initiates new top growth from rootstocks each spring and dies back each fall. It produces vigorous new growth and is thus sensitive to air pollutants over the entire growing season from about April 1 through September 30.

White pine is found naturally in protected locations and is widely grown in plantations in the generating station area. White-pine needles are most sensitive to air pollution injury while they are elongating, which occurs during a 2-week period in late June and early July. Needles normally last for 2 or 3 yr and are moderately sensitive to pollution injury during warm weather, whenever conditions are favorable for rapid rates of photosynthesis. The symptoms on needles can therefore represent cumulative pollution-injury effects.

Lichens are small, undifferentiated plants that are two organisms, an alga and a fungus, growing together in close association for the benefit of both. They lack the specialized tissues of higher plant, such as stems and leaves, and have very different mechanisms for controlling air pollutant entry into the cells. In general, lichen growth rates are far slower than those of higher plants, and particular tissues may be active and subject to pollution injury for several years. Thus, lichens are good bioindicators of chronic low-level pollution effects. The lichens chosen for this study were those that grow on the bark of black oak trees, a common tree in the generating station area.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

AIR POLLUTION MONITORING

The continuous monitoring for sulfur dioxide (SO_2), ozone (O_3), and nitrogen oxides (NO_x) around the Columbia Generating Station indicated that levels of air pollutants were not high enough to cause serious injury or damage to plants. Emissions from the generating station caused ground-level fumigations of SO_2 at concentrations of 50 to 350 $\mu g/m^3$ that usually persisted for only 2 to 3 h. Emissions caused concentrations of NO and NO_2 at ground level that were less than one-half the concentrations of SO_2. Fumigations occurred only on an average of twice each month with a trend toward a greater number of fumigations in the leeward direction from the generating station but with no consistent pattern at certain sites or in particular months of the year. Background concentrations of SO_2 and NO_x were higher than the total amounts of SO_2 and NO_x emitted from the generating station. The background concentrations commonly present were in the range of 20 to 150 $\mu g/m^3$ for SO_2 and 10 to 50 $\mu g/m^3$ for NO_x. Background concentrations of O_3 commonly were in the range of 60 to 100 $\mu g/m^3$, with a peak level of 310 $\mu g/m^3$ for a 1-h period.

The combination of elevated concentrations of SO_2 and O_3 is potentially the most injurious pollutant effect. The infrequent occurrence of elevated levels of the two pollutants simultaneously and, particularly, the infrequent occurrence of increases in both pollutants at a time when plants would be highly sensitive, makes it unlikely that emissions from the generating station will have any significant impact on plants.

FIELD BIOASSAYS FOR VEGETATION INJURY

White Pine Sampling

This study produced no evidence that the Columbia Generating Station is affecting eastern white pine in the area. A small percentage of trees (<5%) exhibited needle injury before and during operation of the generating station. This injury apparently resulted from the background levels of O_3 in the air. The extent of injury varied widely from year to year apparently because of variations in O_3 levels in the different years. Two stands, one on the leeward and one on the windward side of the station, exhibited significant increases in tipburn in certain years apparently resulting from either winter or physiological factors other than pollutant effects.

Lichen Sampling

Sampling of lichen communities on oak trees at 29 sites around the generating station in 1974, and again in 1978, did not indicate any significant injurious effects upon lichens caused by the initiation of station operation. No decreases were found in a number of lichen species present or in the frequency of occurrence of the species. Statistically significant changes occurred in distribution of three species, but these species were present on < 10% of the trees sampled so that these changes are of uncertain importance. The two lichen species found on at least 50% of the trees were *Arthonia caesia* (Flot) Korb and *Parmelia subaurifua* Nyl. These species are not known to be sensitive to SO_2 and no significant changes in their distribution were found in this study.

Annual lichen surveys are needed to establish the variation in lichen communities resulting from annual climatic changes.

Alfalfa Sampling

Sampling of 16 alfalfa fields, three times each season, provided no evidence of injurious effects from the generating station. Many different types of injury were evident on the alfalfa leaves, but none appeared similar to injury from SO_2. Alfalfa yields varied greatly among fields and among years. However, no consistent changes in yields were found after the station began operations. Furthermore, no yield decreases were evident in those fields predicted to have the greatest increases in SO_2 from the station.

Sulfur (S) levels in alfalfa leaf tissue collected from plants in 1978--after initiation of operations at the station--were significantly higher than S levels determined for samples collected in 1974. This increase was evident in samples from fields in all directions around the generating station and not just in the easterly, windward direction where emissions from the generating station were predicted to be greatest. This increase was within the range of normal annual variation in S content of alfalfa and well below levels that would cause injury to the leaf tissue. Because a large segment of alfalfa fields in Wisconsin are deficient in S, S additions from the generating station may benefit the crop.

Alfalfa Field Chamber Studies

Comparison of growth and yield of alfalfa in open-top field chambers indicated no measurable effect of the atmospheric level of pollutants on the plants. Growth of the plants in the field chambers was at different rates than growth of plants in open areas, suggesting that the pollution sensitivity of plants in the chambers may be different from the sensitivity in ambient air.

Comparison of the environment of the chambers with the open area demonstrated significant differences in light intensity and evaporation but little difference in air temperature.

Open-top field chambers provide an effective means of determining the effect of ambient air pollutants, but they must be replicated and set up carefully to insure satisfactory operation and reliablity of data. Considerable effort is required to obtain similar air flow between filtered and non-filtered chambers and to maintain the chambers in operable condition continuously during growth of the crop.

CONTROLLED EXPOSURE STUDIES

In laboratory exposures, large differences in sensitivity to pollutants existed among plant species and cultivars. Trembling aspen was the most sensitive species to exposures of SO_2 and O_3. Injury was produced at concentrations of SO_2 that were greater than any levels monitored around the generating station, but the minimum threshold levels for injury from O_3 were found to be less than the high background levels monitored in the generating station area. Cultivars of alfalfa and peas were more sensitive to SO_2 and O_3 than cultivars of mint, beans, and carrots. The threshold sensitivity levels of even the most sensitive cultivars of alfalfa and peas, however, were above the maximum recorded levels for these pollutants around the generating station. For peas, the threshold sensitivity level of the combination of SO_2 plus O_3 was only slightly greater than the maximum monitored levels of these two pollutants. Since simultaneous elevated levels of the two pollutants were found to occur infrequently, the chance of injury from the combination of pollutants was highly improbable.

The threshold sensitivity levels established for plants in the controlled environment studies are likely at the maximum sensitivity level that will be found under field conditions. This is because the plants grown in a controlled environment are maintained under conditions conducive to rapid growth and maximum sensitivity to pollutants. Plants under field conditions will at times be under moisture stress or unfavorable climatic conditions that will reduce stomatal opening and cause reduced sensitivity to atmospheric levels of pollutants.

SECTION 3

AIR POLLUTION MONITORING NEAR THE COLUMBIA GENERATING STATION

The air-monitoring network has provided continuous data on pollutants that affect plants. The data include sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which are pollutants emitted from the generating station, and ozone (O_3), which is present as a background pollutant in the atmosphere.

MATERIALS AND METHODS

Continuous SO_2 monitors were installed in 1973 at four sites near the Columbia Generating Station: Messer (7.7 km west of the station), Dekorra (4.3 km south-southwest of the station), Lake George (6.1 km east of the station), and Portage Cemetery (9.8 km north of the station) (Figure 1, Figure 2). Locations for these sites were chosen by representatives of the power companies that were constructing the station in conjunction with project staff from the University of Wisconsin-Madison. Two additional SO_2 monitors were installed in June 1976 at the Russell site (15.6 km northeast of the station) and the Bernander site (14.4 km east of the station). At that time the monitor at the Cemetery site was transferred to the Genrich site (8.3 km north of the station) so that SO_2 from the generating station could be separated from SO_2 from sources in Portage. At the same time the Dekorra site was moved about 100 m south to a more open area.

During April 1976, an NO_x monitor was installed at the Lake George site. This monitor was moved to the Genrich site in June 1976.

An oxidant monitor was installed at the Messer site in May 1973 and was replaced by an O_3 monitor in May 1976. An O_3 monitor also was installed at the Genrich site in June 1976.

Several instruments and methods of analysis were used for the different pollutants (Table 3). The SO_2 analyzer and one O_3 analyzer are owned and maintained by the power companies. One O_3 analyzer and the NO_2 monitor are owned and maintained by the Plant Damage subproject. All monitors and recorders are maintained in air-conditioned shelters provided by the power companies.

Since July 1976 maintenance and checking of the instruments have been carried out twice weekly. The instruments have been audited weekly using monitors with calibrations that are traceable to standards of the U.S. Bureau of Standards. During the first 4 yr of the project (1973 to 1976) maintenance of the instruments was less regular and procedures were not as carefully defined as during 1976 to 1978; consequently, the accuracy and

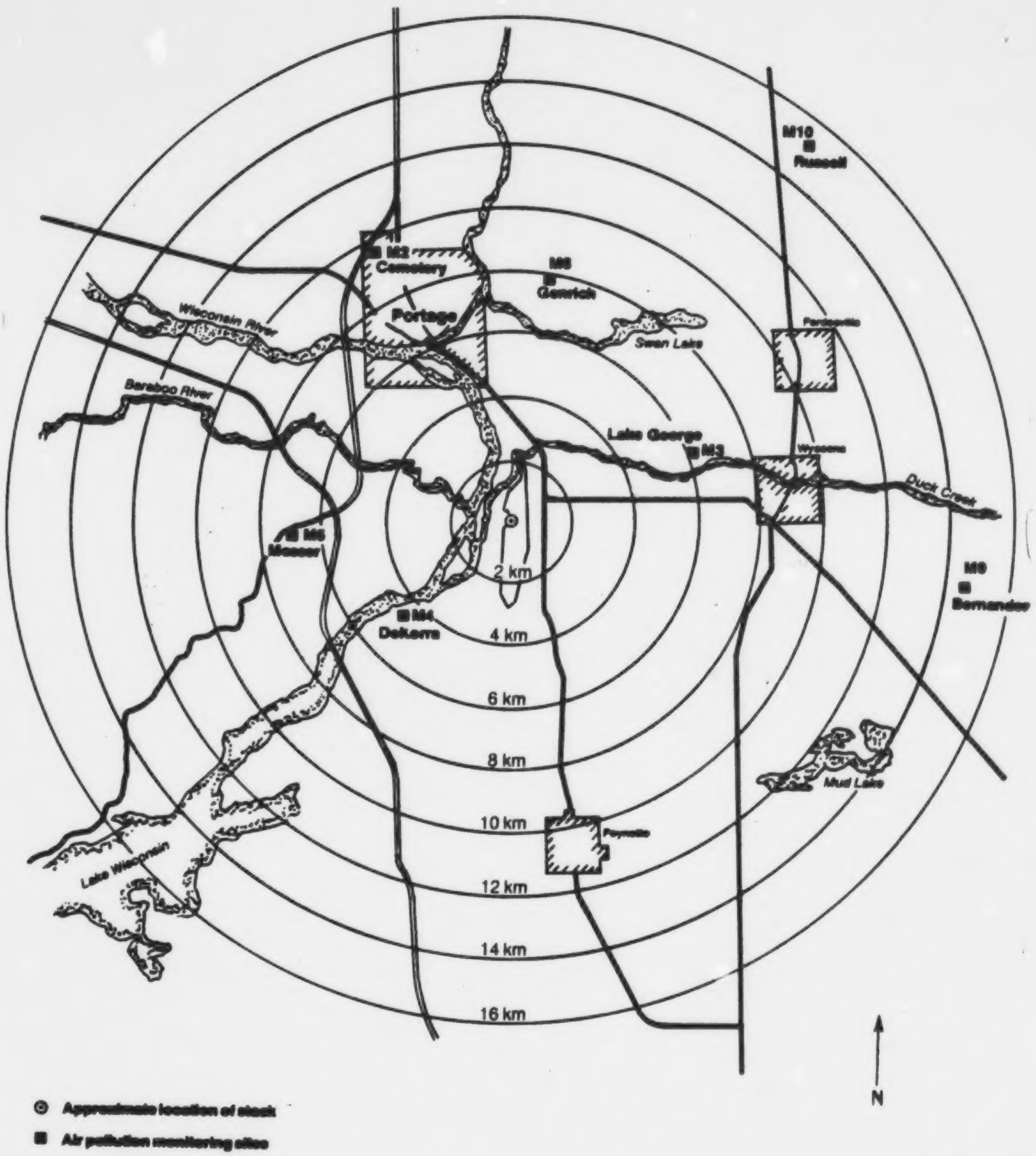

M10
Russell
M2
Cemetery
M8
Genrich
Portage
Wisconsin River
Swan Lake
Pardeeville
Baraboo River
Lake George
M3
Wyocena
Duck Creek
M5
Messer
M4
DeKorra
M9
Bemander
2 km
4 km
6 km
8 km
10 km
12 km
14 km
16 km
Poynette
Mud Lake
Lake Wisconsin
N
Approximate location of stack
Air pollution monitoring sites

Figure 1. Location of air pollution monitoring sites around the Columbia Generating Station.

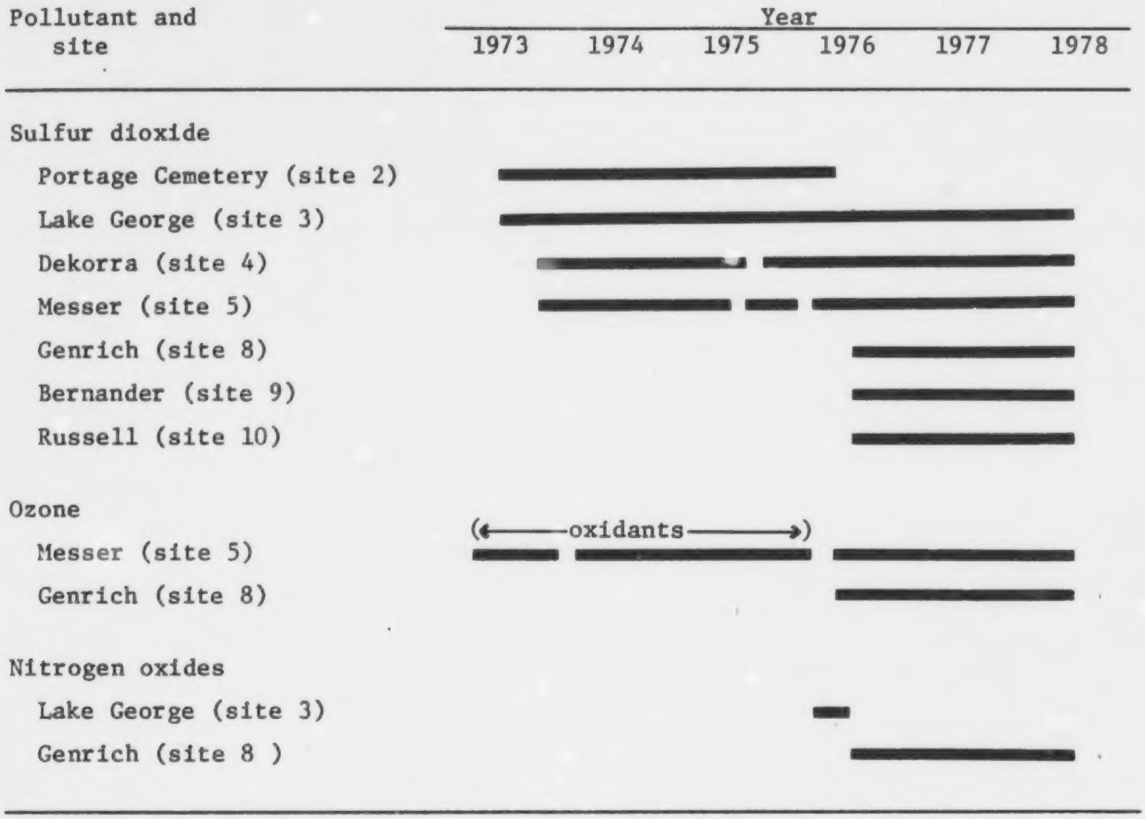


Figure 2. Periods of operation for continuous air-pollution monitors near the Columbia Generating Station. Bars signify periods of operation, and breaks indicate periods of inaccurate data or instrument repair.

precision of the values obtained from 1973 to July 1976 are not as good as data obtained since July 1976.

TABLE 3. INSTRUMENTS USED FOR CONTINUOUS AIR-POLLUTANT MONITORING

Pollutant and site	Instrument	Recording range (ppm)	Method
SO_2			
All sites before May 1978	Phillips PW 9720	0-1.0	Coulometric
All sites after May 1978	Meloy 285	0-1.0	Flame photometric
NO_x			
Lake George	Monitor Labs 8440	0-0.2	Chemiluminescent
Genrich	Monitor Labs 8440	0-0.2	Chemiluminescent
O_3			
Messer before May 1976	Mast 724-2 (Oxidant)	0-0.2	Coulometric
Messer after May 1976	Monitor Labs 8410A	0-0.2	Chemiluminescent
Genrich	Meloy 350	0-0.2	Chemiluminescent

The instruments were operated continuously and data were removed from the recorders as average hourly values. The data were placed on data cards and were summarized by computer to obtain average hourly values for 3-h, 24-h, and 1-month periods.

Data from SO_2 charts were compiled by staff of the Department of Forestry at the University of Wisconsin-Madison from June 1973 through October 1975, by staff of the Institute for Environmental Studies at the University of Wisconsin-Madison from November 1975 through February 1976, and by staff at the Dames and Moore Co. after 1 March 1976. Data from NO_2 charts were compiled by staff of the Department of Horticulture at the University of Wisconsin-Madison for the entire period of record. Data from the oxidant and O_3 charts from the Messer site were assembled by staff of the Department of Horticulture and from the Genrich site by staff at the Dames and Moore Co. for the entire period of the study.

Climatological data were obtained at two sites: the Messer site (8 km W of the station) and the Lake site (3 km directly S of the station). At the Messer site, on the ridge W of the station, monitoring was conducted on towers at 30 m and 90 m above the top of the ridge, which produced measurements at the heights of the two stacks. Monitoring at the Lake site was at the level of the base of the generating station. The prevailing winds near the generating station are westerly, with summer winds predominating from the SW and winter winds from the NW (Figure 3).

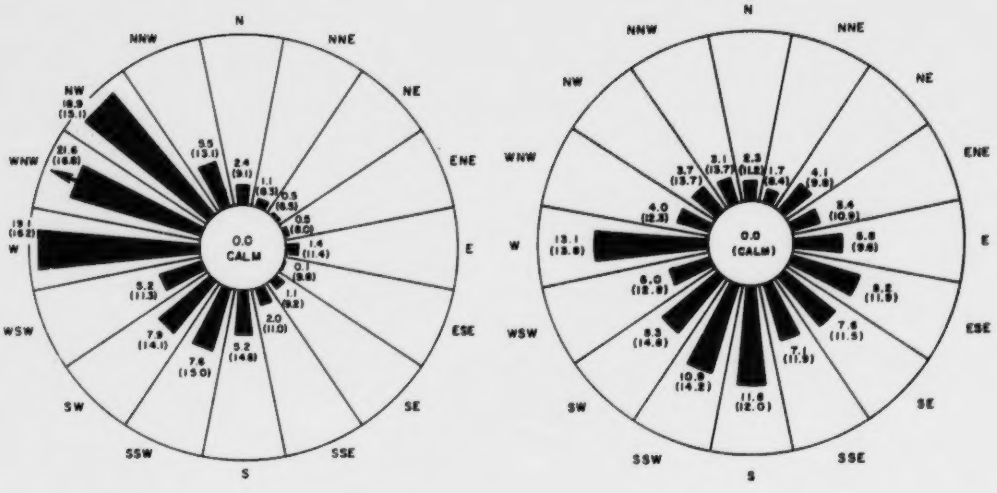
RESULTS

Sulfur Dioxide

The average levels of SO_2 for the years before and after operation of the generating station are shown in Table 4. Data for individual months are provided in Appendix A. This summary indicates an increase of at least two-fold in SO_2 concentrations at all sites from 1976 to 1978 compared to the 1974 to 1975 period. However, this large increase does not truly reflect increased SO_2 in 1976, but is caused by a change in the procedures for reporting data that occurred about the same time as the generating station began operations. From January 1974 through February 1976 when recorded concentrations of SO_2 were at or below the lower limit of sensitivity (5 $\mu g/m^3$) of the instruments, zero was recorded for the hourly intervals. After February 1976, however, a value of 5 $\mu g/m^3$ was recorded for levels at or below the lower limit of sensitivity of the instruments. This procedure was required by the Wisconsin Department of Natural Resources. Thus, since SO_2 is below detectable limits of the recordings most of the time, the reported average concentrations for each month increased greatly after February 1976. Accurate determination of increases in average SO_2 concentrations after operation of the generating station cannot be derived from these data.

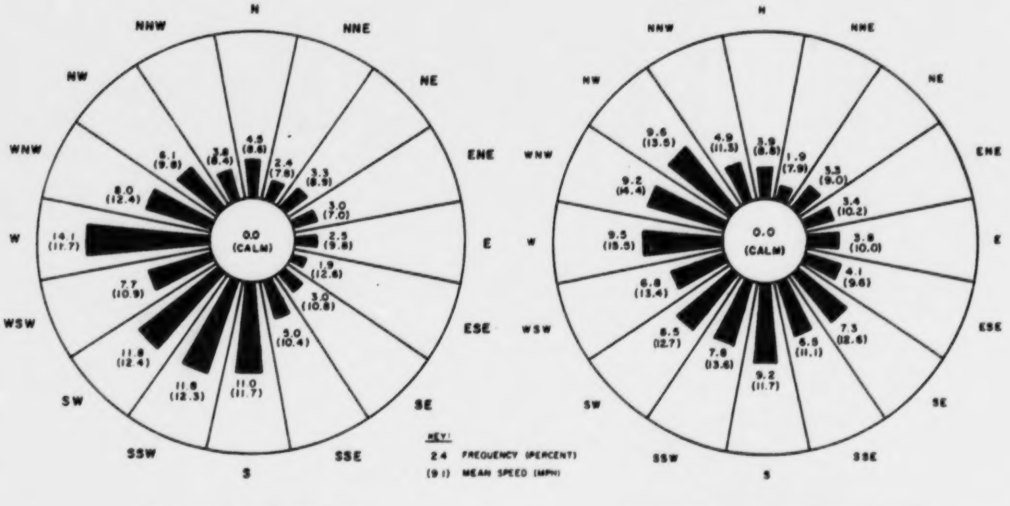
A summation of the frequency of occurrence of all different concentrations of SO_2 for a yearly period (1977) indicates that 86% of the hourly concentrations were below 20 $\mu g/m^3$ and 96% were below 40 $\mu g/m^3$ (Table 5). Most of the low concentrations were below 10 $\mu g/m^3$, i.e., the minimum sensitivity of the analyzers. Only 10% of the recordings were between 20 and 40 $\mu g/m^3$, 2.4% were between 40 and 60 $\mu g/m^3$, and only slightly more than 2% exceeded 60 $\mu g/m^3$ (≃ 0.02 ppm on a volume/volume basis). The accuracy in these low readings is questionable because the measurement range of the analyzer was very large, from 0 to 2,600 $\mu g/m^3$. The maximum hourly concentration recorded over the period 1973 to 1977 was 389 $\mu g/m^3$ (≃ 0.15 ppm) in May 1977 at the Dekorra site. These data were summarized from 1977 measurements since all sites were in operation in that year and since quality assurance of data was better than in preceding years.

Elevated concentrations above 120 $\mu g/m^3$ (≃ 0.05 ppm) and above 240 $\mu g/m^3$ (≃ 0.10 ppm) were separated from the data and tabulated for each site for all years of data collection (Table 6, Table 7). Although few hourly intervals had concentrations above these levels, a greater percentage of concentrations exceeded these levels after the generating station began operation. The percentage of these elevated levels that probably resulted from emissions from the generating station was determined by examination of climatological data to establish if the wind was blowing toward the site from the direction of the generating station at the time of each elevated



DECEMBER 1,1976 — FEBRUARY 28,1977

MARCH 1,1977 — MAY 31,1977



JUNE 1, 1977 — AUGUST 1, 1977

SEPTEMBER 1, 1977 - NOVEMBER 30, 1977

Figure 3. Percentage of winds occurring in indicated directions for four periods during 1977 at the Messer monitoring site located 7 km w of the Columbia Generating Station located at a height of 30 m above the ground at the level of the 195-m stack of the station (provided by the Wisconsin Power and Light Company from quarterly reports prepared by Dames and Moore Inc.).

TABLE 4. SEASONAL AVERAGE CONCENTRATIONS OF SO_2 ($\mu g/m^3$) FOR 1974 TO 1978 AT CONTINUOUS MONITORING SITES NEAR THE COLUMBIA GENERATING STATION*

Year	Cemetery (site 2) 10 km N	Lake George (site 3) 6 km E	Dekorra (site 4) 4 km SSW	Messer (site 5) 8 km W	Genrich (site 8) 8 km N	Bernander (site 9) 14 km E	Russell (site 10) 16 km NE
SUMMER (APRIL--SEPTEMBER)							
1973	4.3 (4,392)	5.3 (4,392)	8.2 (2,208)	2.4 (4,392)			
1974	2.2 (3,588)†	1.9 (3,672)	3.0 (2,304)	1.8 (3,792)			
1975	3.3 (4,008)	7.0 (3,840)	6.3 (2,736)	2.6 (3,192)			
1976		12.4 (3,639)	15.7 (4,195)	17.1 (4,354)	10.9 (3,312)‡	11.2 (2,879)‡	8.6 (3,450)‡
1977		9.8 (3,845)	8.9 (4,228)	8.8 (4,164)	10.5 (4,335)	11.5 (3,881)	9.3 (4,332)
1978		9.0 (2,105)	9.8 (1,927)	9.7 (2,089)	9.8 (1,982)	7.3 (2,090)	8.7 (2,060)
WINTER (JANUARY--MARCH AND OCTOBER--DECEMBER)							
1973	6.5 (2,952)	4.8 (2,952)	4.1 (2,208)	3.6 (2,952)			
1974	5.8 (4,104)	4.5 (4,080)	6.6 (3,744)	4.9 (4,200)			
1975	7.0 (4,164)	6.4 (3,552)	8.4 (3,288)	4.3 (7,464)			
1976		13.5 (3,995)	10.5 (4,033)	9.0 (3,507)	10.6 (2,186)	9.6 (2,186)	9.2 (2,182)
1977		13.3 (4,221)	11.1 (4,094)	15.6 (3,992)	10.6 (4,089)	12.4 (4,173)	12.9 (4,174)
1978§		12.2 (1,992)	10.0 (2,102)	15.4 (2,084)	13.5 (1,985)	13.3 (2,053)	13.4 (2,027)

*All concentrations after February 1976 are elevated over previous data because all measured concentrations < 10 $\mu g/m^3$ (and including 0 $\mu g/m^3$) were recorded as 10 $\mu g/m^3$.

†Numbers in parentheses are hours of valid data for each period.

‡No data before 1 May 1976.

§No data after 30 June 1978.

concentration. This examination demonstrated that < 50% of the elevated levels over 120 μg/m^3 occurred when the winds were in the direction from the generating station. These percentages compared closely with directional plottings of elevated concentrations made with 1976 data and were reported in the annual summary of the Columbia Generating Station for the Wisconsin Power and Light Co. prepared by the Dames and Moore Co. However, the calculations made by Dames and Moore were for concentrations over 100 μg/m^3 (Figure 4). For the hourly-interval concentrations that exceeded 240 μg/m^3 at the different sites, the wind was in a direction to move the plume to the sites for all the elevated concentrations except for the high concentrations recorded at the Messer site (Table 7). The high concentrations at the Messer site occurred with strong southerly winds during cold winter days. The highest levels of fumigations ascribed to the station occurred at sites within 8 km of the station. The highest concentrations of 389 μg/m^3 (≈ 0.15 ppm) were recorded at the Dekorra site, 5 km SSW of the station. No levels exceeding 240 μg/m^3 were recorded at sites 14 and 16 km from the station.

TABLE 5. FREQUENCY DISTRIBUTION OF HOURLY AMBIENT SO_2 CONCENTRATIONS AT ALL MONITORING SITES FOR 1977

SO_2 concentration intervals (μg/m^3)	Period of time (%)	Hours ≥ interval (%)
0-19	85.6	100.0
20-39	9.9	14.5
40-59	2.4	4.6
60-79	1.0	2.2
80-99	0.5	1.2
100-119	0.3	0.7
120-139	0.2	0.3
140-159	0.1	0.2
≥160	0.1	0.1

The duration and frequency of SO_2 fumigations at the sites varied greatly (Table 8). The duration of fumigation was most commonly 3 to 5 h, and the average number of days with fumigations per month at a site was 1.8 (range of 1.3 to 2.3 days at the separate sites). Fumigations were defined as periods when the concentration at a site exceeded by 50 μg/m^3 the average concentration at the other monitoring sites and the wind direction was ± 45° from the station toward the site. Wind direction was obtained by measuring devices at the Messer site at the height of the stacks and at the cooling lake at ground level. If either wind measurement indicated that the plume was directed toward the site, an elevated level was considered a fumigation. The number of fumigations was variable, ranging from a monthly maximum of 9 days with fumigations at the Dekorra site in May 1976 and at

TABLE 6. NUMBER OF HOURLY AVERAGE $SO_2 \geq$ LEVELS 120 $\mu g/m^3$ (≈ 0.05 ppm) AT CONTINUOUS AIR MONITORING SITES NEAR THE COLUMBIA GENERATING STATION

Year	Cemetery (site 2) 10 km N	Lake George (site 3) 6 km E	Dekorra (site 4) 4 km SSW	Messer (site 5) 8 km W	Genrich (site 8) 8 km N	Bernander (site 9) 14 km E	Russell (site 10) 16 km NE
SUMMER (APRIL--SEPTEMBER)							
1974	5 (3,588)*	0 (3,672)	2 (2,304)	3 (3,792)			
1975	1 (4,008)	8 (3,840)	5 (2,736)	0 (3,192)			
1976		18 (3,639)	49 (4,195)	9 (4,367)	19 (3,309)†	2 (3,450)†	5 (3,421)†
1977		1 (3,845)	8 (4,228)	4 (4,164)	6 (4,335)	4 (4,332)	13 (4,077)
1978		0 (2,105)	14 (1,927)	2 (2,089)	11 (1,982)	0 (2,090)	1 (2,060)
WINTER (JANUARY--MARCH AND OCTOBER--DECEMBER)							
1974	13 (4,104)	0 (4,080)	1 (3,744)	4 (4,200)			
1975	4 (4,164)	8 (3,552)	3 (3,288)	2 (4,272)			
1976	2 (1,248)	30 (4,008)	9 (4,030)	6 (3,507)	10 (2,170)†	1 (2,184)†	3 (2,186)†
1977		27 (4,221)	15 (4,094	35 (4,059)	8 (4,089)	34 (4,174)	12 (3,967)
1978		0 (1,992)	0 (2,102)	5 (2,084)	0 (1,985)	1 (2,053)	2 (2,027)

*Numbers in parentheses indicates number of total hours examined.
†No data before May 1976.
No data after June 1978.

TABLE 7. NUMBER OF HOURLY AVERAGE SO_2 LEVELS $\geq$ 240 µg/m^3 (≈ 0.09 ppm) CONTINUOUS AIR MONITORING SITES NEAR THE COLUMBIA GENERATING STATION

Year	Cemetery (site 2) 10 km N	Lake George (site 3) 6 km E	Dekorra (site 4) 4 km SSW	Messer (site 5) 8 km W	Genrich (site 8) 8 km N	Bernander (site 9) 14 km E	Russell (site 10) 16 km NE
SUMMER (APRIL--SEPTEMBER)							
1974	1*	0	0	0			
1975	0	2	0	0			
1976		1	5	1	3†	0†	0†
1977		0	4	0	0	0	0
1978		0	2	0	3	0	0
WINTER (JANUARY--MARCH AND OCTOBER--DECEMBER)							
1974	0	0	0	1			
1975	0	0	0	0			
1976	0	0	0	0	1†	0†	0†
1977		3	0	3	0	0	0
1978		0	0	0	0	0	0

*Number of total hours examined to obtain hours above 240 µg/m^3 were the same as for 120 µg/m^3 (Table 6).

†No data before May 1976.

No data after February 1976.

No data after June 1978.

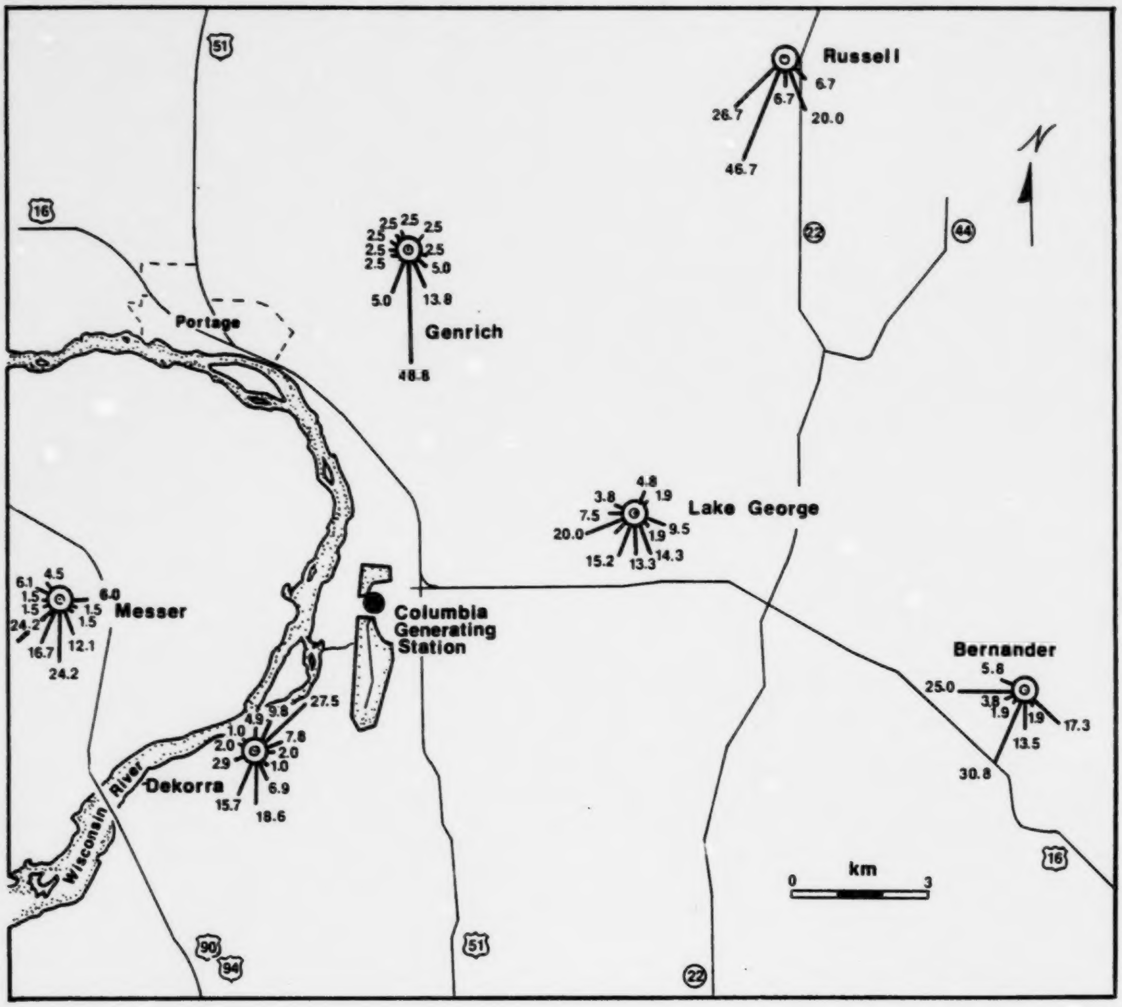

51
Russell
6.7
6.7
26.7
20.0
46.7
N
16
2.5
2.5
2.5
2.5
2.5
2.5
2.5
5.0
5.0
13.8
Genrich
48.8
22
44
Portage
Lake George
4.8
3.8
1.9
7.5
9.5
20.0
1.9
15.2
13.3
14.3
6.1
4.5
6.0
1.5
1.5
1.5
1.5
1.5
24.2
16.7
12.1
24.2
Messer
Columbia
Generating
Station
Bernander
5.8
25.0
3.8
1.9
1.9
17.3
13.5
30.8
9.8
27.5
4.9
1.0
7.8
2.0
2.0
2.9
1.0
Dekorra
6.9
15.7
18.6
River
Wisconsin
km
0
3
16
90
94
51
22

Figure 4. Percentage of hourly-average SO_2 levels over 100 $\mu g/m^3$ occurring with wind from the indicated direction at each continuous monitoring site near the Columbia Generating Station from 1 March 1976 to 28 February 1977 (adapted from the Wisconsin Power and Light Company from the 1976 Annual Report prepared by Dames and Moore, Inc.).

the Bernander site in January 1977 to no fumigations at any site in certain months.

TABLE 8. NUMBER OF DAYS WITH FUMIGATIONS OF SO_2 AT MONITORING SITES NEAR THE COLUMBIA GENERATING STATION FROM MAY 1976 THROUGH JUNE 1978*

Site	Total (days)	Monthly average (days)	Period with valid data (%)
Lake George	49	1.9	91
Dekorra	55	2.1	95
Messer	35	1.3	96
Genrich	60	2.3	94
Bernander	55	2.1	96
Russell	34	1.3	93

*A fumigation was defined as the occurrence for at least a 1-hr period of concentration at one site that exceeded by 50 $\mu g/m^3$ the average concentration at the other sites during a time when the wind direction was ± 45° from the Columbia Generating Station toward the site.

The background levels of SO_2 contributed significantly to the total SO_2 monitored at the sites. Elevated background SO_2 levels of 20 to 100 $\mu g/m^3$ were recognized by the increases in levels that occurred simultaneously at all sites. Measurable background levels were almost always present when winds were blowing from the SE, S, or SW, and the concentrations tended to increase with increasing wind velocities. Significantly greater background SO_2 occurred during the winter than during the summer (Table 9). The highest background levels were found at the Messer site, which was located on an elevated ridge about 150 m higher than the other sites. Monthly averages of data for all years and sites are provided in Appendix A.

Estimates of the average background level of SO_2 were obtained by using averages from monitors at sites that were not in the direction of plume movement from the stack. The monthly background SO_2 levels were 15 to 20 $\mu g/m^3$ during December and January and 2.5 to 3.5 $\mu g/m^3$ during July and August (Table 10). The average background concentrations shown in Table 10 include only recorded values that were $\geq$ 10 $\mu g/m^3$. The corrected values of Table 10 were calculated because whenever values of < 10 (including values of $\leq$ 0) were recorded, a value of 5 was tabulated for concentrations of SO_2 in the air. Thus the calculated average values in Table 9 generally have a high bias, because during a majority of the time there is no measurable SO_2 in the generating station area.

TABLE 9. AVERAGE HOURLY SO_2 CONCENTRATIONS ($\mu g/m^3$) BY MONTH AT MONITORING SITES NEAR THE COLUMBIA GENERATING STATION IN 1977

Month	Lake George (site 3) 6 km E	Dekorra (site 4) 4 km SSW	Messer (site 5) 8 km W	Genrich (site 8) 8 km N	Bernander (site 9) 14 km E	Russell (site 10) 16 km NE	Average
January	20.8 (744)*	16.1 (744)	24.5 (742)	16.9 (744)	21.0 (740)	16.9 (727)	19.4
February	11.6 (672)†	7.8 (672)	9.2 (672)	8.9 (672)	12.0 (672)	9.7 (672)	9.9
March	9.3 (740)	9.0 (729)	8.7 (701)	10.0 (735)	10.4 (738)	9.1 (741)	9.4
April	10.7 (696)	11.5 (711)	9.5 (701)	13.1 (707)†	9.6 (647)	11.6 (694)	11.0
May	9.8 (744)	12.6 (657)	11.0 (744)	13.3 (744)†	9.5 (692)	10.5 (741)	11.1
June	12.7 (698)	8.6 (660)	8.2 (678)	10.6 (713)	9.2 (708)	10.6 (708)	10.0
July	13.7 (330)	7.0 (740)	8.2 (737)	7.1 (719)	12.8 (744)	8.8 (744)	9.2
August	7.7 (712)	6.6 (744)	7.4 (695)	10.9 (744)	18.3 (741)	7.1 (732)	9.7
September	6.1 (665)	7.5 (716)	8.4 (609)	7.7 (708)	8.5 (545)	7.7 (713)	7.6
October	7.8 (673)	7.3 (730)	8.2 (733)	7.5 (733)	9.1 (702)	12.0 (730)	8.7
November	15.9 (679)	11.7 (527)	22.3 (519)	7.5 (520)	9.4 (703)	14.1 (590)	13.4
December	13.8 (713)	14.8 (692)	23.1 (692)	11.8 (685)	12.5 (422)	15.7 (714)	15.3

*Numbers in parentheses are hours of valid data for each month.

†Concentrations are increased significantly because of inaccurate analyzer calibration during these months.

Concentration lower than other sites because analyzer was inoperable during extended periods of high background levels that were recorded at other sites.

TABLE 10. CORRECTED AVERAGE MONTHLY SO_2 CONCENTRATIONS AT CONTINUOUS MONITORING SITES NEAR THE COLUMBIA GENERATING STATION IN 1977*

Month	Lake George (site 3) 6 km E	Dekorra (site 4) 4 km SSW	Messer (site 5) 8 km W	Genrich (site 8) 8 km N	Bernander (site 9) 14 km E	Russell (site 10) 16 km NE	Average
January	18.5 (744)†	13.0 (744)	22.4 (742)	13.7 (744)	18.4 (740)	13.4 (727)	16.6 (4,441)
February	8.1 (672)	3.6 (672)	5.4 (672)	4.9 (672)	8.3 (672)	5.8 (672)	6.0 (4,032)
March	5.5 (740)	5.0 (729)	4.4 (701)	6.1 (735)	6.7 (738)	5.0 (741)	5.4 (4,384)
April	7.8 (696)	7.6 (711)	5.5 (701)	10.4 (707)	6.5 (647)	7.9 (694)	7.6 (4,156)
May	6.1 (744)	8.4 (657)	7.1 (744)	10.8 (744)	5.6 (692)	6.9 (741)	7.5 (4,322)
June	9.2 (698)	4.3 (660)	3.9 (678)	6.6 (713)	5.3 (708)	6.6 (708)	6.0 (4,165)
July	11.0 (330)	2.6 (740)	4.1 (737)	2.8 (719)	9.1 (744)	4.8 (744)	5.2 (4,014)
August	3.8 (712)	2.2 (744)	3.4 (695)	7.2 (744)	15.1 (741)	2.6 (732)	5.8 (4,368)
September	1.8 (665)	3.4 (716)	4.6 (609)	3.7 (708)	4.3 (545)	3.4 (713)	3.5 (3,956)
October	3.7 (673)	3.2 (730)	4.3 (733)	3.4 (733)	5.1 (702)	8.8 (730)	4.8 (4,301)
November	13.0 (679)	8.1 (527)	19.2 (519)	3.4 (520)	5.3 (703)	10.6 (590)	9.8 (3,538)
December	10.4 (713)	12.4 (692)	20.5 (692)	8.4 (685)	8.9 (422)	12.5 (714)	12.3 (3,851)

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*All recorded concentrations of 10 $\mu g/m^3$ or less were not added to the value. Ten $\mu g/m^3$ was the minimum threshold sensitivity level of the instruments and therefore reported for all recorded concentrations at this level or below.

†Numbers in parentheses are hours of valid data for each month.

Concentrations are increased because of inaccurate calibrations.

Concentrations lower than other sites because analyzer was inoperative during extended period of high background levels which were recorded at other sites.

The average monthly concentrations at any individual site tended to vary significantly from other sites depending upon the frequency and persistence of plume fumigations at that site. For example, approximately twice as much SO_2 from the station was recorded at the Lake George site in July and at the Bernander site in August 1977 than at the other sites (Table 10). These increases from generating station activity at these sites produced an average monthly increase of 7 to 8 $\mu g/m^3$ of SO_2. During most months, however, the frequency and persistence of fumigations were low, and average concentrations apparently increased < 1 $\mu g/m^3$ at individual sites.

Nitrogen Oxides

The data for NO_x measurements were obtained primarily from the Genrich site, 8 km N of the station, for 1976, 1977, and 1978. These data are incomplete because of the difficulties of maintaining the analyzers in an operating mode and in known calibration. A summary of the frequency occurrence of different concentrations for 1977 (the year with the most complete data) indicates that most of the time little measurable NO and < 20 $\mu g/m^3$ of NO_2 ($\simeq 0.01$ ppm) were recorded (Table 11). Very few hours of NO levels over 40 $\mu g/m^3$ ($\simeq 0.03$ ppm) and of NO_2 levels over 80 $\mu g/m^3$ ($\simeq 0.04$ ppm) were recorded. The maximum recorded levels were 47 $\mu g/m^3$ for NO and 101 $\mu g/m^3$ for NO_2.

Comparisons of elevated NO_x levels with SO_2 levels during periods of obvious fumigations from the generating station indicated that combined NO_x was about 50% of SO_2 concentrations at the Genrich monitoring site 8 km N of the generating station. Most of the measured NO_x did not result from station emissions because the wind was not blowing from that direction during most periods of elevated NO_x. Measurable NO_x occurred primarily during extended periods of southerly winds apparently moving NO_x-laden air masses from urban areas such as Madison, Chicago, Beloit, Moline, and possibly St. Louis. The levels of NO_2 in these southerly winds were higher than the levels of NO, indicating that the source of the NO_x was sufficiently distant to provide time for conversion of NO to NO_2. The few recorded instances of elevated levels of NO and NO_2 resulted from automobile traffic in the nearby city of Portage (population 8,000) and from heavily-traveled highways 5 km W and 10 km SW of the monitoring site. The elevated levels from the highways were noted particularly between 8 pm and midnight on weekends of heavy vacation travel when the wind was in an appropriate direction.

Ozone

Ozone data were obtained with oxidant meters before May 1976 and with chemiluminescent O_3 analyzers for the remainder of 1976 and for 1977. Table 12 and Table 13 summarize data for the Messer and Genrich sites, respectively, for the entire period of 1973 to 1977 and therefore include data obtained with both types of analyzers. Comparison of readings taken with both types of analyzers during April through August 1976 demonstrated that oxidant levels averaged 22% less than O_3 values, but that this difference varied considerably, and that during some periods oxidant levels were even higher than O_3 levels. Since comparisons in Texas (Severs 1975)

TABLE 11. FREQUENCY DISTRIBUTION OF HOURLY AVERAGES OF NO, NO_2, AND NO_x CONCENTRATIONS DURING 1977 AT THE GENRICH SITE (SITE 8, LOCATED 8 KM N OF THE COLUMBIA GENERATING STATION)

	NO		NO_2		NO_x	
Concentration interval range ($\mu g/m^3$)	Hours recorded (%)	Hours $\geq$ interval (%)	Hours recorded (%)	Hours $\geq$ interval (%)	Hours recorded (%)	Hours $\geq$ interval (%)
0-19	98.7	100.0	75.7	100.0	65.8	100.0
20-39	1.0	1.3	20.9	24.3	27.7	33.6
40-59	0.3	0.3	2.0	3.4	4.1	5.9
60-79	0.0	0.0	0.8	1.3	0.8	1.8
80-99			0.5	0.6	0.6	1.0
100-119			0.03	0.03	0.4	0.5
120-139					0.1	0.1
Total number of hours of valid data	4,409		3,517		3,329	

indicated even greater differences between these procedures, the data obtained with oxidant meters before May 1976 cannot be directly compared with O_3 concentrations monitored since that date.

The data in Table 12 and Table 13 demonstrate significant levels of O_3 in the air most of the time. The high levels of O_3 occur primarily with winds from the SE, S, and SW, and apparently result from the large amount of automobile travel in urban areas and highways S of the station. The highest levels occur during spring and early summer when light duration and intensity are at a maximum. Lowest levels occur during fall and early winter when light duration and intensity are at a minimum.

Although trends in high and low levels in different months were similar at the two sites, the levels at the Messer site (Table 12) were slightly higher than levels at the Genrich site (Table 13). The higher levels at Messer might be anticipated because this site is located on a ridge about 150 m above the Genrich site. At the higher elevation, wind velocities were greater and O_3 levels apparently were not reduced as much by surface scrubbing as at the lower elevation Genrich site. In addition, where air movement was in directions to move automobile exhaust from Portage and the interstate highway over the Genrich monitoring site, the O_3 levels at that site dropped to zero apparently as a result of NO reaction with O_3. This did not occur at the Messer site because of its elevated location above the highway.

Frequency of occurrence of different concentrations of O_3 was recorded for the Genrich and Messer sites in 1977 (Table 14). The highest frequencies were for concentrations between 40 and 79 $\mu g/m^3$ (0.02 and 0.04 ppm) at both sites and during all seasons. Levels above the air-quality standard of 235 $\mu g/m^3$ (0.12 ppm) occurred $< 0.2\%$ of the time. Most of the elevated levels occurred during the growing season (April through September), with maximum levels usually occurring in May. The actual number of hours for the 27 months from April 1976 through June 1978 for which O_3 concentrations exceeded 160 $\mu g/m^3$ (0.08 ppm) was 279 h at Genrich (site 8) and 783 h at Messer (site 5) (Table 15). Concentrations of 200 $\mu g/m^3$ (0.10 ppm) were exceeded during 55 h at Genrich and 145 h at Messer, and concentrations of 240 $\mu g/m^3$ (0.12 ppm) were exceeded for only 11 h at Genrich and 11 h at Messer. The maximum 1-h average concentration recorded at both sites was 310 $\mu g/m^3$ (0.155 ppm) at Genrich in July 1977.

CONCLUSIONS

Although measurable increases in SO_2 have been documented after initiation of operations at the generating station, no levels have been recorded that would produce significant damage to plants. Elevated levels of SO_2 from the generating station have not exceeded 390 $\mu g/m^3$ ($\approx$ 0.15 ppm) for any 1-h period at any measuring site, and levels in excess of 240 $\mu g/m^3$ ($\approx$ 0.10 ppm) occurred during no more than five hourly intervals per year at any site and did not occur at sites located more than 10 km from the generating station. The occurrence at any one site of increased SO_2 levels from the generating station was extremely variable, and an average effect from the station could not be determined with data obtained for only 2 yr.

TABLE 12. AVERAGE MONTHLY O_3 CONCENTRATIONS ($\mu g/m^3$) FOR MAY 1973 THROUGH JUNE 1978 AT THE MESSER SITE (SITE 5, LOCATED 8 KM W OF THE COLUMBIA GENERATING STATION)

Month	1973	1974	1975	1976	1977	1978
January		28 (437)*	25 (294)	37 (701)	68 (738)	62 (724)
February		46 (248)	51 (53)	58 (530)	92 (667)	77 (412)
March		38 (292)	56 (380)	65 (368)	83 (557)	99 (709)
April			91 (584)	82 (582)	84 (391)	84 (710)
May	58 (662)†	41 (141)	96 (542)	111 (743)‡	102 (743)	103 (718)
June	63 (720)	51 (58)	89 (391)	129 (669)	86 (537)	100 (529)
July	68 (732)	46 (301)	78 (735)	121 (736)	99 (573)	
August	65 (740)	44 (286)	67 (500)	117 (535)	81 (731)	
September	58 (714)	55 (104)	48 (666)	91 (621)	65 (713)	
October	28 (730)	37 (467)	55 (695)	77 (738)	64 (678)	
November	27 (504)	24 (641)	41 (407)	59 (702)	42 (697)	
December	39 (156)	22 (272)	29 (342)	55 (741)	44 (694)	

*Numbers in parentheses are hours of valid data for that month.

†Data from May 1973 through April 1976 were obtained with a Mast oxidant meter.

‡Data from May 1976 through 1978 were obtained with a chemiluminescent O_3 analyzer.

TABLE 13. AVERAGE MONTHLY O_3 CONCENTRATIONS ($\mu g/m^3$) FOR MAY 1976 THROUGH JUNE 1978 AT THE GENRICH SITE (SITE 8, LOCATED 8 KM N OF THE COLUMBIA GENERATING STATION)

Month	1976	1977	1978
January		55 (740)	53 (662)
February		68 (672)	68 (642)
March		70 (739)	93 (706)
April		88 (719)	78 (689)
May	89 (460)*†	103 (534)	93 (711)
June	104 (670)	79 (705)	86 (690)
July	78 (711)	73 (668)	
August	58 (735)	47 (715)	
September	56 (714)	40 (684)	
October	47 (717)	37 (661)	
November	41 (717)	34 (689)	
December	50 (728)	38 (712)	

*Number in parentheses are hours of valid data for that month.

†All data were obtained with a chemiluminescent O_3 analyzer.

TABLE 14. FREQUENCY DISTRIBUTION OF HOURLY AVERAGE O_3 CONCENTRATIONS FOR 1977

Concentration interval range ($\mu g/m^3$)	Hours recorded (%)	Hours $\geq$ interval (%)	Hours recorded (%)	Hours $\geq$ interval (%)
	Messer (site 5)*			
	(April-September)		All year	
0-19	1.1	100.0	4.6	100.0
20-39	5.4	98.9	8.9	95.4
40-59	17.2	93.5	21.3	84.5
60-79	22.0	76.3	21.4	63.2
80-99	22.7	54.3	19.2	41.7
100-119	15.8	31.6	13.4	22.5
120-139	7.7	15.7	4.7	9.1
140-159	4.5	8.1	2.4	4.4
160-179	2.3	3.6	1.2	2.0
180-199	1.0	1.3	0.5	0.8
200-219	0.2	0.5	0.1	0.3
220-239	0.1	0.2	0.1	0.2
240-259	0.03	0.04	0.01	0.1
$\geq$260	0	0	0.01	0.1
	Genrich (site 8)†			
	(April-September)		All year	
0-19	8.3	100.0	11.2	100.0
20-39	15.1	91.7	18.1	88.8
40-59	18.1	76.6	22.8	70.8
60-79	21.0	58.5	22.7	47.9
80-99	16.1	37.4	13.3	25.3
100-119	10.9	21.3	6.7	12.0
120-139	5.5	10.5	2.8	5.3
140-159	2.4	4.9	1.2	2.5
160-179	1.2	2.6	0.6	1.3
180-199	0.8	0.3	0.4	0.6
200-219	0.3	0.5	0.2	0.3
220-239	0.1	0.2	0.05	0.1
240-259	0.1	0.1	0.04	0.1
$\geq$260	0.1	0.1	0.02	0.02

*Site 5 is located 8 km W of the Columbia Generating Station.
†Site 8 is located 8 km N of the Columbia Generating Station.

TABLE 15. HOURS WHEN O_3 CONCENTRATIONS EXCEEDED SPECIFIED LEVELS: SEASONAL DISTRIBUTION IN 1976, 1977 AND 1978 (JANUARY TO JUNE)

	> 160 μg/m^3		> 200 μg/m^3		> 240 μg/m^3	
	Messer (site 5)	Genrich (site 8)	Messer (site 5)	Genrich (site 8)	Messer (site 5)	Genrich (site 8)
1976						
January-March						
April-June	235	51	51	20	0	2
July-September	260	42	62	10	3	2
October-December	28	5	10	0	5	0
1977						
January-March	5	0	1	0	1	0
April-June	75	98	10	20	1	4
July-September	57	6	3	2	0	1
October-December	0	0	0	0	0	0
1978						
January-March	33	20	1	0	0	0
April-June	90	57	7	3	1	2

Background levels of SO_2 contributed more total SO_2 to the area than did fumigations from the generating station. When present, background SO_2 concentrations were between 20 and 100 $\mu g/m^3$ ($\approx$ 0.01 to 0.04 ppm); the maximum concentration for an hourly interval at one site was 285 $\mu g/m^3$ ($\approx$ 0.11 ppm). The total contribution of background SO_2 was greater than for the generating station because a greater number of hours of elevated background levels occurred and because all sites received elevated levels concurrently whereas fumigations from the generating station usually affected only one site at a time.

Increases in NO_x levels were measured after operation of the generating station, but these were at low levels. Maxima of 47 $\mu g/m^3$ (0.03 ppm) of NO and 101 $\mu g/m^3$ (0.05 ppm) of NO_2 were measured at the single monitoring site, 7 km N of the generating station. The background level of NO_x also was quite low and of no particular significance.

The elevated O_3 levels monitored in the area are potentially of greatest concern when they occur concurrently with elevated SO_2 levels. The infrequent occurrence of high O_3 levels and SO_2 levels, however, makes it quite unlikely that high elevated levels of the two pollutants will occur concurrently.

SECTION 4

FIELD STUDIES NEAR THE COLUMBIA GENERATING STATION

SAMPLING WHITE PINE STANDS

Introduction

Eastern white pine (*Pinus strobus* L.) was chosen as a bioindicator species for study of the environmental impact of the Columbia Generating Station because of its sensitivity to sulfur dioxide (SO_2) and its widespread occurrence in the area. Permanent sample plots in stands of eastern white pine near the power plant were monitored for 8 yr, beginning during the 1971 growing season, i.e., 4 yr before the station began operations.

Eastern white pine has long been known for its susceptibility to what variously has been called emergence tipburn, chlorotic dwarf, semimature needle blight, needle blight, or white-pine blight. Hepting (1968) indicated that all these disorders are in fact the same disease, now called tipburn. Costonis and Sinclair (1969), Dochinger et al. (1969), Dochinger and Seliskar (1970), and Houston (1970) showed that symptoms of tipburn are caused by gaseous pollutants, specifically ozone (O_3) and SO_2. Tipburn occurs on a small percentage of white pines in most areas of the United States resulting principally from O_3 in the atmosphere. Tipburn has been observed on white pines in stands throughout Wisconsin (A. Prey, personal communication).

Evaluation of damage to white pine has been based primarily on foliar symptoms. Foliar markings on the tips of white pine needles caused by O_3 and SO_2 consist of silver-grey flecks on the stomatal surface which enlarge to pink spots and then coalesce to form chlorotic bands (Houston and Stairs 1973). These bands develop into reddish-brown necrotic areas at the tips of the needles. The necrotic areas may vary in length from < 1 mm to several centimeters but are usually 1 to 2 cm in length. Severity of tipburn injury can vary from tree to tree and from year to year. The most severely injured trees have stunted tops, short needles, and poor needle retention. Concentrations of SO_2 and O_3 in the range of 0.05 ppm (125 $\mu g/m^3$ for SO_2 and 100 $\mu g/m^3$ for O_3) have been shown to injure sensitive white pines in controlled exposures of 4 h (Costonis 1973, Houston and Stairs 1973, Houston 1974).

Methods

White pines were selected for monitoring in 1971. Aerial photographs of Columbia County were obtained from the Agricultural Stabilization and Conservation Service of the U.S. Department of Agriculture to locate white-pine stands surrounding the power plant site. Most stands were selected directly from these photographs followed by ground observation. Stands near high-voltage power lines, near houses, or with unusual exposure were avoided whenever possible. Stands near roads were especially avoided because of the possibility of injury from road salting. Stands generally were chosen with exposure to wind from at least one direction, for accessibility, and for minimum likelihood of being cut down or altered in the near future. Fifteen suitable sites were chosen to provide a random sampling of the area in all directions within a 12 km radius of the station (Figure 5 and Table 16). At sites with < 100 trees, all trees were monitored. At the larger sites, trees were monitored if their position could be accurately documented, and if they could be observed from the base to the tip on at least one side. Thus, trees in rows and particularly those on outside rows were commonly selected for monitoring. The position of each tree to be sampled was documented. A label was attached to the first tree in each row, and all trees in each row were numbered. Detailed maps of all sampling sites are shown in Appendix B.

Foliar injury, typical of air pollution injury, was determined for each tree. For each tree, symptoms of air-pollutant injury were differentiated from those caused by other types of environmental stress, disease, insect damage, or human activities. The number of trees with air-pollutant injury was divided by total number of trees to calculate the percentage of injured trees at each site, called the tipburn frequency. In addition to annual fall examinations (late September or early October) other examinations were made during the summers of 1975 and 1977 in response to reports by local residents of noticeable white-pine injury and in June 1978 because of the high frequency and severity of injury at two sites.

During the June 1978 survey, samples of white-pine needles were obtained from several sites for determination of total sulfurs. Samples were taken from the midcrown to upper crown of two to four white pines from sites 2, 4, 5, 6, 7, and 9. The needles were sent to C. Gordon of the University of Montana for S analysis. Separate analyses were conducted on needles that had developed in 1976, 1977, and 1978.

Differences in the percentage of trees injured in individual years were analyzed statistically. An analysis also was made of the difference in injury for the years before (1972 to 1974) and after (1976 to 1977) operation of the generating station. The data in 1971 were omitted because only seven sites were monitored and the data in 1975 because of intermittent pollutant emissions during start-up of the station in the summer of that year. Statistical comparisons also were made for differences between sites before and after operation. The analysis was extended to compare sites on the basis of average annual increase in SO_2 predicted at each site as a result of generating station operation (Ragland and Goodell, in press). For the analysis, white pine sites were rated 1, 2, or 3, depending on whether

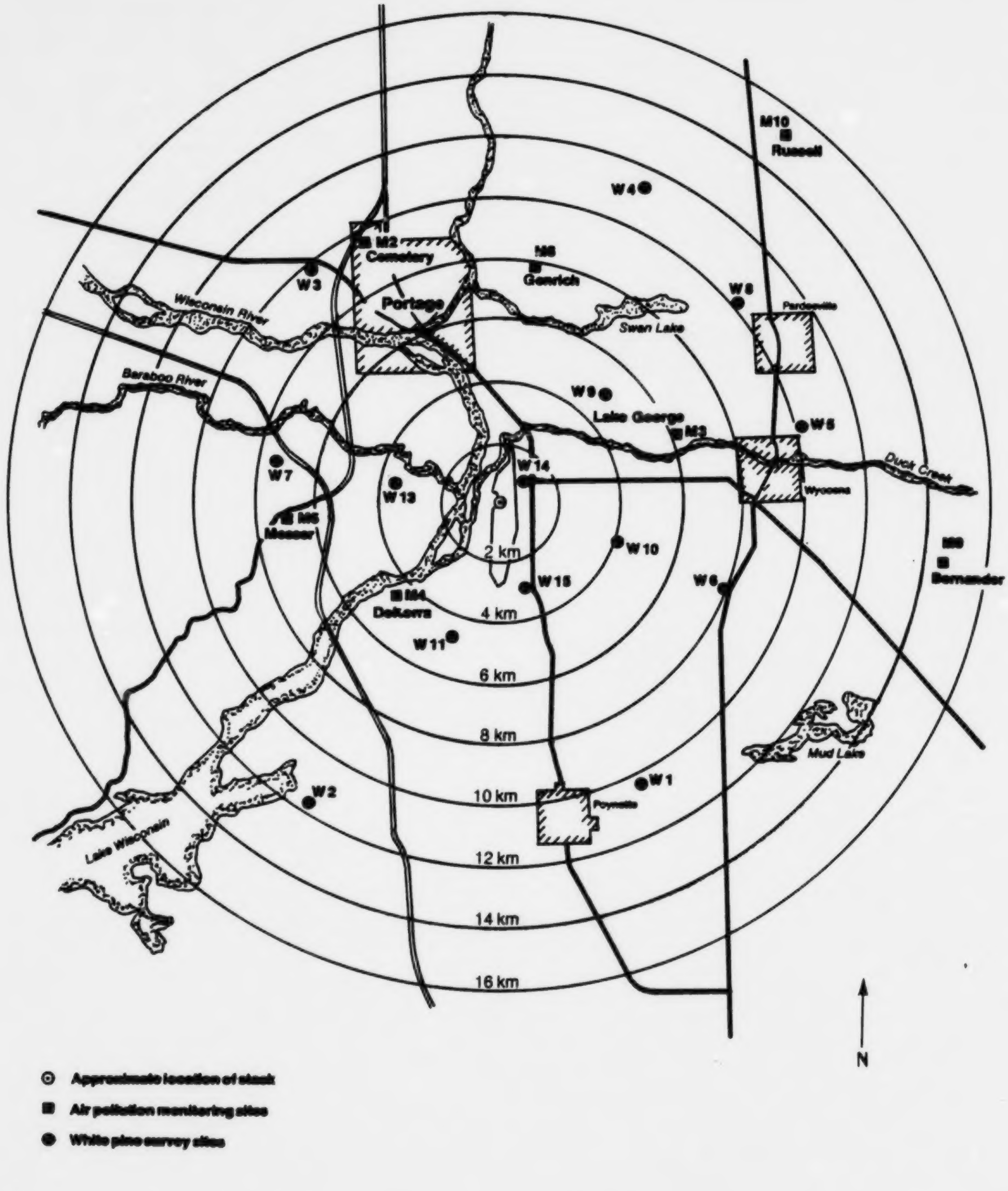

M10
Russell
W4
M1
M2
Cemetery
M6
Genrich
W3
Portage
Wisconsin River
Swan Lake
W8
Pardeeville
Baraboo River
W9
Lake George
M3
W5
Duck Creek
W14
Wyocena
W7
W13
M5
Messer
2 km
W10
M9
Bernander
W15
W6
M4
DeKorra
4 km
W11
6 km
8 km
Mud Lake
W1
10 km
W2
Poynette
Lake Wisconsin
12 km
14 km
16 km
N
Approximate location of stack
Air pollution monitoring sites
White pine survey sites

Figure 5. Location of white pine and air monitoring sites around the Columbia Generating Station.

TABLE 16. DESCRIPTION OF WHITE PINE MONITORING SITES

Site	Distance from generating station (km)	Approximate age of the stand (yr)	Number of trees sampled	Exposure*
1	11.3 SSE	15,40	355	Open
2	10.5 NW	20	100	Closed
3	12.1 NE	10,20	199	Open
4	10.5 E	35	20	Open
5	8.1 SE	25	141	Open
6	7.2 SW	15	76	Closed
7	8.1 WNW	15	30	Open
8	8.9 NE	15	50	Open
9	4.8 NE	35	114	Open
10	4.4 SE	20	62	Closed
11	4.8 SSW	15	77	Open
12	3.2 SW	20	27	Open
13	4.0 NW	15	100	Closed
14	0.8 NW	20	41	Open
15	2.8 SSW	20	138	Closed

*Open sites have trees exposed fully to the wind from at least one direction. Underlining indicates sites open toward the generating station.

†These plots are made up of two stands with the ages shown.

‡Site 3 had 242 trees before a fire in 1976.

they received 1 to 2 µg SO_2 (0.0004 to 0.0008 ppm), 2-3 µg SO_2 (0.0008 to 0.0012 ppm), or 3 to 4 µg SO_2 (0.0012 to 0.0016 ppm) (Figure 6).

Results and Discussion

Tipburn injury was found on an average of 2.5% of the white pines at the monitoring sites before operation (1972 to 1974) and during 2 yr of operation of the generating station (1976, 1977) (Table 17) indicating that tipburn injury has not changed with station operation. Although certain trees tend to be injured year after year at each site, the number of trees injured at each site varied considerably from year to year.

The variations in injury from year to year result apparently from differences in the sensitivity of white pines and of differences in pollutant levels from year to year. The low amount of injury during 1976 was likely associated with the unusually dry conditions from June to September of the year. The lack of rain would reduce the susceptibility of the needles to air pollutants. The increased injury during 1975 was associated with favorable growing conditions and increased concentrations of O_3 during the early summer period (Table 12) when needles were most sensitive to pollution.

No differences were detected in the occurrence or type of symptoms on pines before and after initiation of the station. The most common type of air-pollution injury found was a reddish-brown dieback (0.1 to 3 cm in length) of needle tips. The severity of injury varied from tree to tree and from year to year. The most severely injured trees had stunted tops, short needles, and poor needle retention. Tipburn injury developed during the summer months as the needles were elongating. In the study area, budbreak and the initiation of needle growth for eastern white pine generally occur in the first few weeks of June. Thus, the sensitive time for the needles is from early June to the end of the summer growing period, with maximum sensitivity during needle elongation in June and early July.

Monitoring of SO_2 and O_3 around the generating station (Table 5, Table 14) showed that levels of both pollutants were at concentrations that could cause injury to white pines (Costonis and Sinclair 1969, Costonis 1970 and 1973, Houston 1974). It was assumed that the pollution injury observed on white pines resulted primarily from background O_3 levels because the frequency of potentially injurious concentrations was considerably greater for O_3 than for SO_2.

Because lower levels of combined amounts of SO_2 and O_3 have produced greater injury than either pollutant alone (Costonis 1973, Houston 1974), this mixture is of greatest concern. Because elevated levels of O_3 are limited primarily to days when winds are from the southwest, south, or southeast, the combination of O_3 and SO_2 concentrations from the generating station would likely occur and cause injury only in pine stands located north of the generating station.

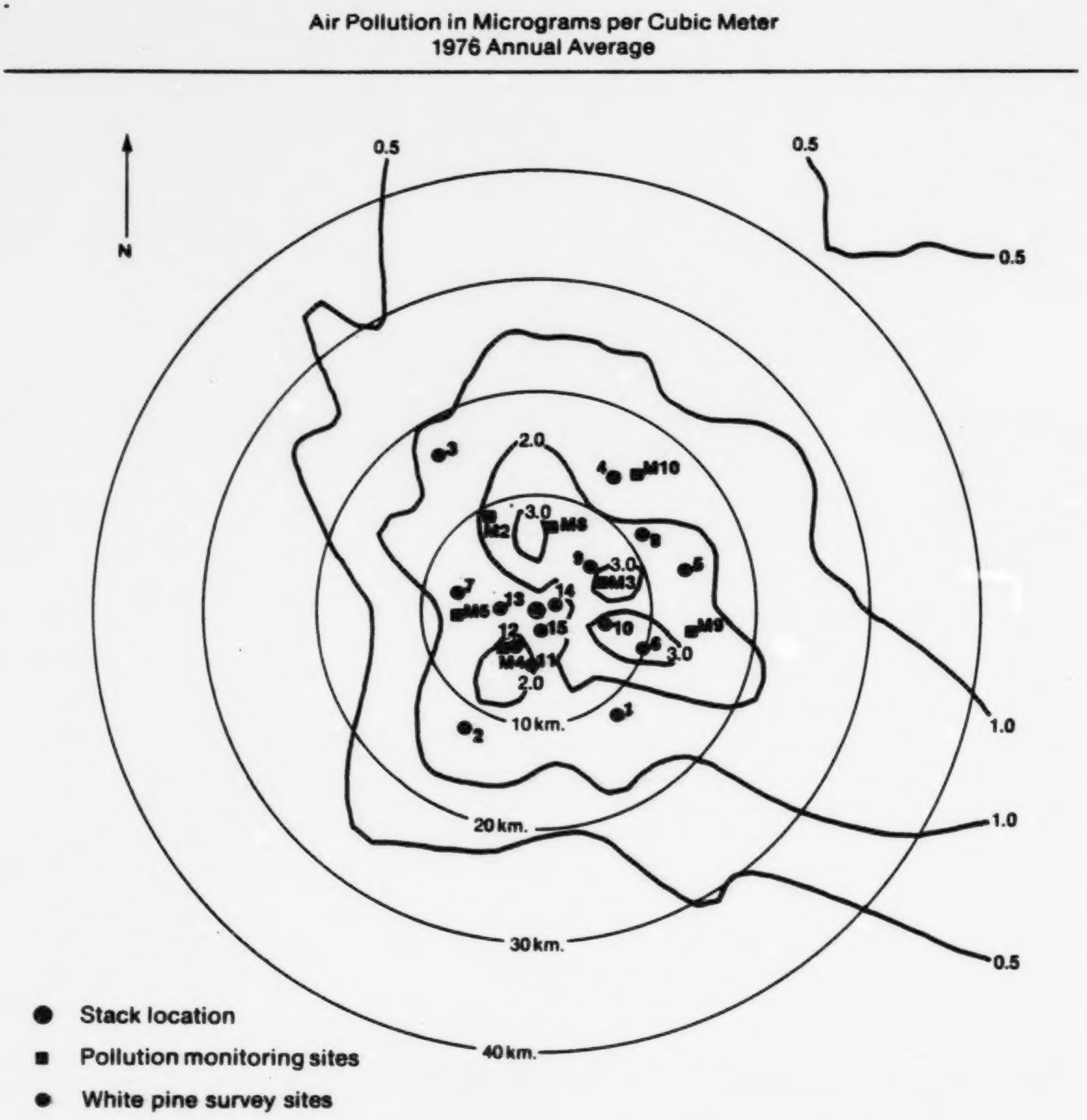

Air Pollution in Micrograms per Cubic Meter
1976 Annual Average
N
0.5
0.5
0.5
3
2.0
4
M10
3.0
M2
M8
8
9
3.0
5
M3
7
14
13
M5
12
15
10
M9
M4
11
6
3.0
2.0
1
2
10 km.
1.0
20 km.
1.0
30 km.
0.5
40 km.
● Stack location
■ Pollution monitoring sites
● White pine survey sites

Figure 6. White pine survey sites around the Columbia Generating Station and isopleths of predicted ground level SO_2 ($\mu g/m^3$) as a result of generating station operations.

TABLE 17. FREQUENCY OF TIPBURNED EASTERN WHITE PINE IN SAMPLE PLOTS SURROUNDING THE COLUMBIA GENERATING STATION (% TREES INJURED)

		Before operation of generating station					With operation of the generating station			
Site	Distance from generating station (km)	Fall 1971	Fall 1972	Fall 1973	Fall 1974	Average* 1972 to 1974	Fall 1975†	Fall 1976	Fall 1977	Average 1975 to 1977
1	11.3 SSE	-	2.0	4.5	2.2	2.9	5.7	1.4	2.3	3.1
2	10.5 NW	-	3.0	8.0	14.0	8.3	4.0	3.0	2.1	3.0
3	12.1 NE	-	0.0	0.0	0.0	0.0	1.2	1.0	0.5	0.9
4	10.5 E	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	8.1 SE	-	2.1	1.4	4.3	2.5	2.8	0.0	3.5	2.1
6	7.2 SW	7.9	3.9	2.6	2.6	3.0	5.3	1.3	3.9	3.5
7	8.1 WNW	-	6.7	6.7	0.0	4.5	6.7	0.0	0.0	2.2
8	8.9 NE	-	8.0	6.0	2.0	5.3	1.0	0.0	2.0	1.3
9	4.8 NE	7.9	1.8	0.9	0.0	0.9	10.5	0.0	7.9	6.1
10	4.4 SE	-	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
11	4.8 SSW	-	0.0	0.0	0.0	0.0	3.9	0.0	0.0	1.3
12	3.2 SW	0.0	0.0	7.4	7.4	4.9	3.7	0.0	7.1	3.6
13	3.0 NW	3.0	2.0	6.0	1.0	2.7	6.0	0.0	4.0	3.3
14	0.8 NE	7.4	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.8
15	2.8 SSE	2.2	0.7	0.7	1.4	0.9	4.3	0.7	0.0	1.7
Average		5.1	1.8	2.7	2.4	2.5‡	4.3	0.8	2.3	2.3‡

*1971 tipburn figures are not included in averages.

†Station operation began in June 1975 and was operating at full capacity by 1 August 1975; therefore, needle growth in 1975 was completed before the station was in full operation.

‡No significant difference in annual averages before and with operation of the Columbia Generating Station.

A severe form of injury with different symptomology from that caused by air pollutants developed in 1977 at site 9, i.e., 5 km NE of the generating station. Needles on a group of adjacent trees at one edge of the stand developed a necrotic injury that extended 3 to 6 cm from the tip rather than the 1 to 2 cm for common tipburn injury. Some 25 to 50% of the needle length was often necrotic on injured trees. The portion of the stand with injured trees was found to be over a very high water table, which probably led to physiological injury of the needles. The high water table would produce a waterlogged soil with poor aeration so that the trees would be particularly subject to needle desiccation and injury during hot days with high transpiration rates. Although the high water table could have increased the pollution sensitivity of the trees, the severe injury to all trees in the area and to the adjacent trees of red pine that are more resistant to pollutants makes this hypothesis questionable.

During spring 1978, severe injury developed on 1-yr old needles on many trees at several different sites. An unusually high degree of winter injury was prevalent on coniferous trees throughout Wisconsin in spring 1978 and apparently was a contributing factor. At site 9—5 km NE of the generating station--an additional increase in injury was observed and most needles on several of the trees injured during 1977 were completely necrotic. The high water table at this site persisted through the spring. Site 7, 8 km W-NW of the generating station, also exhibited a high degree of injury in spring 1978, and the water table there also was very close to the surface during this time.

The S analyses of samples of white pine needles taken from six sites (2, 4, 5, 6, 7, and 9) in June 1978 did not indicate any significant differences in S levels at pine stands in different directions from the generating station or any significant correlation with the amount of tipburn injury seen at the sites (Table 18). The results of this sampling were not conclusive because of the large variation in S levels between trees at the same site. Additional analyses should be undertaken in future studies with a larger number of trees sampled at each site and more careful selection of the sampling location on each tree to insure uniformity in samples.

BIOASSAY EVALUATION

Species Selection

The selection of white pines for sampling--although providing a sensitive monitor for SO_2--was complicated because white pines also are sensitive to O_3 and the symptomology of the injuries from the two pollutants is quite similar. Thus, accurate background data to document the amount of injury from O_3 was a necessary part of this study. Because of the large year-to-year variation in injury, however, more than 3 yr of background data were needed to make an accurate assessment.

Trees in plantations were preferred to naturally-seeded trees because they usually were planted at the same time and hence were more uniform in size. The plantation trees also were more readily accessible and were planted in rows so that individual trees were easier to locate at sampling times. A disadvantage of such trees is increased disease and insect damage caused by their close spacing. Close spacing also enhances competition between trees for light, water, and nutrients.

TABLE 18. The S CONTENT (PPM) OF WHITE-PINE NEEDLES HARVESTED IN 1978 FROM SELECTED SAMPLING SITES

Site	Tree sampled	1977	1976	1975	1974
2	A	1,450	1,050	1,100	1,000
	B	1,350	1,150	950	
4	A	1,200	1,300	950	
	B	1,200	700	600	
5	A	1,200	1,250	900	
	B	1,200	1,050	850	
	C	1,150	1,350	1,150	
	D	950	950	1,100	
6	A	1,450	1,450	1,150	
	B	1,200	1,050	1,050	
7	A	1,450	1,550		
	B	1,150	1,200		
9	A	1,550	1,550		
	B	1,300	800		

Selection of Sampling Sites

Identification of white pine stands from aerial photographs was an effective procedure for locating potential sampling sites because characteristics of this species could be separated readily from those of broadleaf trees and because few other coniferous species existed in the area. If a broadleaf species had been selected for the bioassay, identification of stands would have been more difficult because of the similar foliage characteristics of the different broadleaf species growing in the area.

The 15 sites provided 3 to 4 sampling sites in any 90° quadrant out from the generating station. A larger number of sites would have been desirable because of the large differences in tree age and exposure to winds from particular directions in the different stands. Additional sites in the area with solid stands of at least 25 white pines between 15 and 50 yr old, however, were not available when the study began.

Sampling Procedures

Tipburn resulting from air pollutants could be differentiated from other diseases because of the position of injured trees within a stand, the position of injured needles within each tree, and the type of needle symptom. Tipburn injury usually occurred only on new needles during the summer in which they developed. Older needles are relatively resistant to air pollutants.

The similarity between needle-injury symptoms caused by different pollutants is a significant uncertainty in the use of white pines to determine the effects of air pollutants. A brown dieback of needle tips is produced by SO_2 and O_3, and the two are nearly impossible to differentiate. Therefore, the tipburn observed on white pines may have been caused by O_3 or SO_2 transported to the area, by SO_2 emitted from the generating station, or by combinations of SO_2 and O_3.

Tipburn was measured only once each year at the end of the growing season. However, for better correlation of injury symptoms to possible pollutant sources, sampling should have been conducted on a more frequent basis. Sampling every month may have resulted in more closely identified times of injury, which could be compared to periods of elevated pollutant concentrations. Determination of the number of trees exhibiting injury at each site was an effective means of obtaining a rapid measurement of injury at each site. Tipburn injury is a reliable criterion for the evaluation of tipburn to white pines in other areas of the United States (U.S. Environmental Protection Agency 1971). The procedure used in this study was reasonably objective and introduced little observer bias. Quantitative measurements of the degree of injury to particular trees may be desirable to permit comparisons of the extent of injury at different sites and in different years. On a quantitative scale, percentage of needle retention might be used to indicate injury from pollutants (Gordon et al. 1978).

Growth-ring analysis provides additional valuable information concerning the effects of SO_2 on white pines by measuring individual annual rings on core samples taken from trees (> 10) at each site (Pollanschutz 1971, Stone and Skelly 1974). These measurements allow an evaluation of total annual impact of pollutants and provide control data prior to pollutional events. Records must be correlated carefully with climatological data to compensate for the effects of particular weather conditions on growth.

Preliminary analyses of S concentrations in white-pine needles indicate that the method may be useful for determining the effects of SO_2 emissions on white pine (Miller and McBride 1975, Gordon et al. 1978). Analysis of needles of different ages shows the relative accumulation of S from SO_2 pollution for different years. Needle samples should be taken from a similar location on all trees and collected at least yearly to allow determination of year-to-year variability. A minimum of four trees should be sampled to obtain an accurate estimate of S content.

White-pine clones, selected for sensitivity to SO_2 are particularly useful for monitoring. Specific clones that are sensitive only to O_3, SO_2, or fluorides have been identified (Berry 1973), and are being used as bioindicators of specific air pollutants. If this clonal material were available, trees sensitive to each pollutant could be planted at each sampling site.

CONCLUSIONS AND RECOMMENDATIONS

No evidence was found that the Columbia Generating Station is affecting the eastern white pine in the area surrounding the station. Instances of increased injury at scattered sites were observed but the data do not indicate that emissions from the generating station are the cause of the injury. It is recommended that the field plots be monitored in spring and fall each year to separate tipburn caused by winter injury (spring survey) and air pollution (fall survey). Systematic studies of the S content of needles and of growth rings of the trunk would provide information on possible impacts from SO_2 in concentrations too low to cause visible injury.

SECTION 5

SAMPLING LICHENS ON OAK

INTRODUCTION

As part of the study of the effects on plants of emissions from the Columbia Generating Station, a project to survey communities of bark lichens was undertaken in 1974--near the site of the station--with support from the Wisconsin Department of Natural Resources (Will-Wolf 1977). Data were to provide a baseline for the bioassay of atmospheric emissions of sulfur dioxide (SO_2) from the station. The Columbia Generating Station began operations in spring 1975. In 1978 the same lichen communities were resurveyed with support from the U.S. Environmental Protection Agency. Lichens have been used frequently in northern Europe and in North America for bioassay of SO_2 (Ferry et al. 1973, LeBlanc and Rao 1975).

Lichens are composed of algae and fungi in symbiosis. A lichen has a relatively undifferentiated plant body called a thallus, which has no leaves, stems, or roots, and lacks the specialized stomata for gas exchange characteristic of vascular plants. Compared with higher plants, lichens have few barriers to water or gaseous pollutant exchange with the air (Hill 1974). Laboratory studies have shown that gaseous and aqueous forms of SO_2 adversely affect photosynthesis and respiration in lichens (Ferry et al. 1973, LeBlanc and Rao 1973, Puckett et al. 1973). Mechanisms of SO_2 interactions in lichen metabolism are complex and only partially understood (Ferry et al. 1973, Puckett et al. 1973, Hill 1974).

Concentrations of gaseous and aqueous SO_2 found to affect lichens in laboratory studies have varied widely, depending on the lichen species, duration of exposure, and physical and chemical conditions affecting the lichens during tests. In particular, the sensitivity of lichens to SO_2 is dependent on moisture availability because of their resistance to dry conditions (Türk et al. 1974), i.e., lichens must be partially hydrated and actively photosynthesizing to be sensitive to SO_2. However, laboratory studies have indicated that lichens are more sensitive when kept under long-term partial hydration than when fully hydrated (Guderian 1977). Injury to fully-hydrated lichens occurred after 14-h exposures to gaseous SO_2 concentrations of 0.17 to 0.50 ppm (442-1,300 $\mu g\ m^{-3}$) (Nash 1973 and 1975, Türk et al. 1974). Long-term exposures of lichen transplants to experimental fumigation with an average of 0.09 ppm (234 $\mu g\ m^{-3}$) SO_2 for 29 days killed all the lichens tested while exposure to 0.03 ppm (78 $\mu g\ m^{-3}$) SO_2 for 68 days damaged an average of 60% of each lichen thallus (Guderian and Schoenbeck 1971). Laboratory exposures of lichens to 0.1 to 0.2 ppm

(130-260 $\mu g\ m^{-3}$) SO_2 for periods of 2 to 28 days also caused injury (O'Hare and Williams 1975).

The disappearance of sensitive lichen species has been documented in areas receiving annual average concentrations of 0.005 to 0.015 ppm (13 to 29 $\mu g\ m^{-3}$) SO_2 around a coal-fired generating station (Showman 1975), and around a group of nickel smelters (Nieboer et al. 1972). These average concentrations are quite low, however, because the lichens were located around point sources, fumigations most commonly would be several fold above this average concentration, and a majority of the time there would be no SO_2 exposure from the source. Eversman (1978) documented sublethal adverse effects to lichens in a field situation resulting from controlled continuous release of SO_2 that provided a 3-month average exposure of 0.0018 ppm (4.7 $\mu g\ m^{-3}$) SO_2 (sulfation plates). Maximum hourly average exposures for Eversman's study sites were 0.60 to 0.65 ppm (1,560 to 1,690 $\mu g\ m^{-3}$), with hourly averages exceeding 0.25 ppm (650 $\mu g\ m^{-3}$) for about 2% of the exposure time (Lee et al. 1979).

Laboratory studies by Guderian and Schonbeck (1971) comparing a SO_2-sensitive European lichen species with several SO_2-sensitive vascular plant species showed that the lichen species were slightly less sensitive than the vascular-plant species to short-term high-SO_2 exposures, but more sensitive to long-term lower levels of SO_2. In a review of laboratory comparisons of lichens with higher plants, Guderian (1977) concluded that these laboratory tests showed lichens were in general about as sensitive to short-term SO_2 exposure as sensitive vascular plants. A review of comparative field studies indicated that lichens may be more sensitive to long-term low levels of SO_2 than are most vascular plants (Guderian 1977). Some reasons for this are the lack of barriers to gas exchange in lichens, their ability to photosynthesize and grow whenever the air temperature is at least a few degrees above freezing, and the persistence of a lichen thallus over many growing seasons.

Lichens also are well-suited to long-term biomonitoring studies because of their permanence at study sites. Lichen growth is normally quite slow. Worldwide, annual radial increments of 0.7 mm to 5.6 mm have been recorded for representative temperature-zone foliose lichens, and even less growth is reported for crustose lichens (Ahmadjian and Hale 1973). Natural community changes from year to year are slight barring large-scale disruptions at a site.

METHODS OF DATA COLLECTION

Selection of Lichen Habitats

Communities of lichens growing on different substrates were evaluated for their potential as useful bioindicators of SO_2 in the area surrounding the station. Lichens growing on the ground were eliminated from consideration for sampling because of their scattered distribution in the area. Rock lichens, although widely distributed in the area, were eliminated because their taxonomy is so poorly known that identification would be difficult. In addition, since the geology of the Portage area is complex and exposed rock strata are not uniform in composition, lichens growing on the rocks would not represent a homogeneous community. Showman (1975) concluded that lichens growing on soil or on rocks are not good indicators of air quality.

Communities of bark lichens were chosen as the most useful for bioassay. Such communities have been studied extensively in Wisconsin (Culberson 1955a and 1955b, Hale 1955) and have been used frequently as indicators of air pollution. The lichen flora of Wisconsin forests is quite rich, with species composition differing considerably according to the different tree species serving as substrates. For this reason, lichen communities growing on a single group of related tree species were selected for the bioassay.

Forest communities in the area surrounding the station vary from river-bottom forest to dry upland forest (Curtis 1959). Consequently, few tree species occur in a wide enough range of habitats to provide an adequate sample at each study site. In addition, some tree species, such as white pine, support a poorer lichen flora than others (Newberry 1974) and these are not the best choices for sampling.

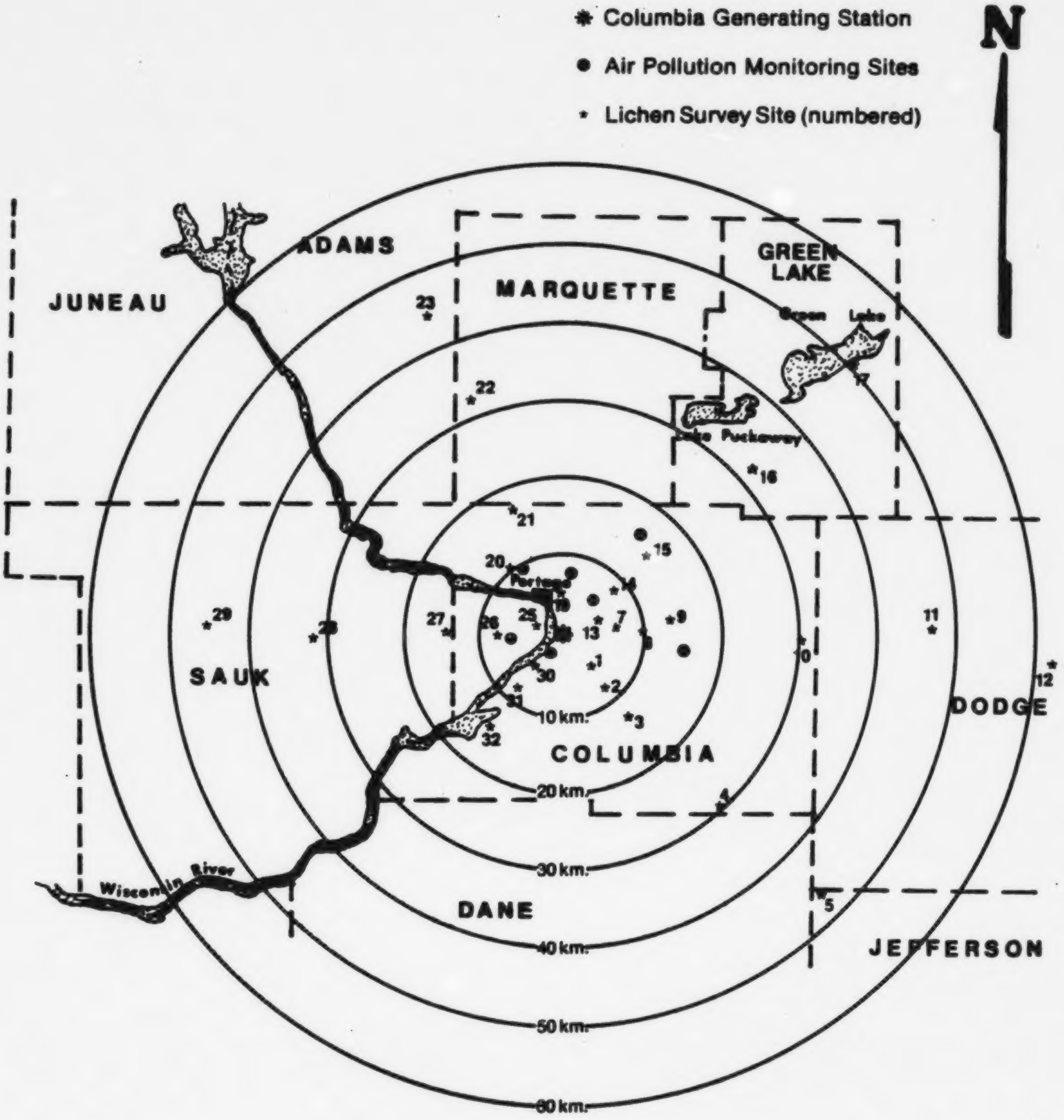
Elms and white and black oaks in the area have rich lichen flora. Since elms are restricted in distribution mostly to river-bottom woods, however, the most appropriate choice of sample tree species was oak. Of the oak species, black oaks were selected because they are more widespread in the area and their bark lasts longer. Three species of black oak occur in the study area and were used as lichen substrates: black oak, (*Quercus velutina*); red oak, (*Q. borealis*); and Hill's oak, (*Q. ellipsoidalis*). Hale (1955) showed that these tree species have similar bark pH and lichen communities.

Site Location

Lichen sites (29) were selected along southeast, east, northeast, north-northwest, west, and southwest transects at approximately 5, 10, 16, 32, and 48 km from the station (Figure 7). Exceptions to this scheme occurred along two transects; one 54 km from the generating station along the E transect; sites were not established at 32 and 48 km along the SW transect. Surveys were made during the winter and spring of 1974 and 1978.

In all cases, actual sites were within 1.5 km of the planned location. Most sites were established in woods of no smaller than 2 ha. Deviations from this pattern are mentioned in detailed site descriptions contained on individual maps of each survey site (Appendix C).

Since several lichen sites are close to continuous SO_2 monitoring stations (Figure 7), data from the latter provide a measure of actual SO_2 levels to correspond with lichen-bioassay results.



Columbia Generating Station
Air Pollution Monitoring Sites
Lichen Survey Site (numbered)
N
JUNEAU
ADAMS
MARQUETTE
GREEN LAKE
Green Lake
Lake Puckaway
SAUK
COLUMBIA
DODGE
DANE
JEFFERSON
Portage
Wisconsin River
10 km.
20 km.
30 km.
40 km.
50 km.
60 km.
1
2
3
4
5
7
8
9
10
11
12
13
14
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Figure 7. Location of lichen and air pollution monitoring sites around the Columbia Generating Station.

Tree Survey

Comparison of the forest stands with each other by use of standard tree-sampling procedures provides a means of establishing the range of variation in tree species at the sites chosen. This procedure was deemed necessary because the lichen vegetation of forest stands in Wisconsin has been shown to vary with species composition of forest vegetation (Culberson 1955a and 1955b, Hale 1955).

At each site, 20 circular sample plots 0.01 ha in size (radius 5.5 m) were established at 15-m intervals in a rectangular grid pattern conforming to the shape of the woods (see site maps, Appendix C). Sides of the grid were walked with a compass so that the grid could be reproduced easily. Trees were located within the circular plots with a standard forester's optical range-finder. All trees larger than 15 cm in diameter at a height of 1.4 m were recorded by species, and their size was determined with a tape marked for conversion of circumference to basal area. Since the tree-species composition of the survey sites is not expected to change very rapidly, the 1974 tree survey was used as a frame of reference for both lichen surveys.

Lichen Sampling

In 1974, 10 black oaks at each site were selected for lichen sampling by examining one tree in every other tree-sample plot. An effort was made to select trees whose basal area was between 645 cm^2 and 1,935 cm^2. No trees smaller than these guidelines were sampled, although in some cases larger trees were used. Locations of trees used for lichen sampling are marked on individual site maps (Appendix C). The tree numbers indicated on these site maps correspond to the permanent number tagged on each tree.

Since lichen flora differ on different sides of the same tree (Newberry 1974), lichen communities at different sites were compared using samples from the same side of each tree. The sampling procedure also took into account the possibility that the effects of SO_2 emissions would be greatest on the sides of trees facing the source of pollution (Newberry 1974).

For each tree sampled, two square quadrats of bark--25 cm on a side--were established permanently, one on the NE-facing side of the tree and the other on the side of the tree facing the generating station. The bottom of each quadrat was placed 1.4 m above the ground. Since both sets of quadrats coincided in sites on the SW transect, only one quadrat per tree was established. Permanent quadrats were marked with an aluminum nail in the lower left corner of each quadrat. A numbered aluminum tag was hung from the nail marking the NE quadrat on each tree, and the number and basal area of each tree were recorded (Appendix C).

In 1974 a photograph was taken of each permanent quadrat. A white card with the tree number and quadrat aspect was tacked directly above the quadrat to be photographed. The other corners of each quadrat were temporarily marked with tacks, which are discernible in the photographs.

All quadrat photographs were taken using Kodak Tri-X black and white 35-mm film.

Directly beneath each permanent quadrat, a 25 x 25 cm area was sampled in 1974 for all bark lichens. The outer bark was removed from the sample quadrat with a hammer and a wood chisel; care was taken not to injure the inner bark of the tree. All visible lichens and large pieces of bark were removed for microscopic examination and stored in paper bags. Each bag was identified in the field by site, date, tree number, and quadrat aspect.

In 1978, the permanent quadrats were located and again photographed. When a previously-sampled tree could not be located or had died, it was replaced with a newly numbered black oak as close as possible to the original tree, and new permanent quadrats were marked and photographed.

Bark samples in 1978 were taken from an unsampled black oak of the proper size, nearest to each numbered tree, using the same procedures as in 1974. The top edge of each sample quadrat was located 1.4 m above the ground, with quadrats facing the same directions as the permanent quadrats.

Laboratory Examinations

Bark samples were examined under a dissecting microscope, and the lichen species present in each quadrat were recorded. Lichens were identified using keys prepared by Fink (1935), Hale (1969), and unpublished keys provided by J. W. Thomson of the Department of Botany at the University of Wisconsin-Madison. Following identification, the number of quadrats in which each lichen species was found at each site was summarized for the two aspects.

Observations on the presence of growth anomalies were recorded for four common lichen species during routine identification of 1978 samples; these observations were not made in 1974. The presence of small white powdery accumulations on the surface of lobe tips of *Parmelia bolliana* (species 22) was recorded. The presence of brown, necrotic areas was recorded for *P. caperata* (sp. 23) and *P. rudecta* (sp. 26). The presence of bleached areas was recorded for *Physcia millegrana* (sp. 35).

Eversman (1978) found evidence of yellowing as a result of SO_2 exposure in lichens that are normally yellow-green in color. Since *P. caperata* (sp. 23), a yellow-green lichen, was common in the study area, one specimen from each quadrat in which the species was found was checked for yellowing by comparing the color of the lobe tips with a standard Munsell Color Chart (1942).

METHODS OF DATA ANALYSIS

Data were analyzed in several ways to describe and compare the lichen communities at the survey sites before the generating station began operation and to provide a basis for determining whether changes in lichen communities at the sites were related to operation of the generating station.

Description of Sites

Tree and lichen communities in 1974 were described using an ordination technique. In addition, a continuum index was calculated for the trees found at each site to relate the species composition of the forest to the range of xeric to mesic growing conditions for Southern Wisconsin upland forests (Curtis 1959).

Ordination is a general term for a group of mathematical techniques used to aid in interpretation of trends and relationships among sites or other elements in large data sets. The function of ordination is to provide a diagram locating the sites (or other entities) so that similar sites are close together and sites which are different are far apart. Such a diagram helps the researcher to identify the ecological causes of similarities and differences among sites or other entities. The ordination method used was devised by Bray and Curtis (1957) and modified by Beals (1960) and Beals, Reichert, and Will-Wolf (unpublished manuscript, Department of Zoology, University of Wisconsin-Madison). The computer program (known as BCORD) is on file in the Department of Botany, University of Wisconsin-Madison.

Sites (or other elements) are compared using numerical attributes selected for each site. These attributes may be almost any quantifiable, descriptive characteristics of the sites being studied. For this study the attributes chosen were numerical estimates of the importance of each tree or lichen species at each site. Definitions of the attributes used are given separately for each ordination. After a set of attributes is chosen and calculated, similarity between any two sites is determined using a formula that provides a single number based on all the attributes for the two sites. The formula used here was based on the Sorenson (1948) index of similarity. Similarities between all pairs of sites are calculated, producing a matrix of values. This matrix is visualized as a set of points in a multidimensional space with the locations of the points (sites) determined by their differences from one another.

Since multidimensional spaces cannot be represented easily on paper and since a matrix of numbers cannot be interpreted easily, an ordination diagram is constructed by projecting the locations of the site points onto one or more (usually three) perpendicular axes. The X-axis of the ordination represents the greatest differences among site points. The Y-axis represents the greatest amount of left-over difference among site points after the X-axis has been constructed, and the Z-axis represents the greatest amount of difference among site-points left over after the X- and Y-axes have been constructed. Since the original distance matrix could have many dimensions, i.e., up to the number of attributes used, three axes seldom express all the differences but can account for the major differences among site-points.

Tree Communities

Tree communities at the 29 survey sites were described using an ordination that compared sites based on the tree species found at each site. The attributes selected for the sites were the importance values for each of the tree species. The importance value for each of the tree species at a site was calculated as the average of three quantities for that species (Curtis and McIntosh 1951): 1. Density (% D), i.e., the number of trees of a species divided by the total number of trees sampled at each site; 2. frequency (% F), i.e., the number of sample plots at which a tree species occurred divided by the summed number of sample plots at which each tree species occurred; and 3. dominance (% Do), i.e., the summed basal area of all sampled trees of a species divided by the summed basal area of all trees sampled at each site.

The continuum index (CI) for each site was obtained by summation of relative values derived by multiplying the importance value of each tree species at a site by a climax-adaptation value established for each species (Curtis 1959).

Lichen Communities

Lichen communities at survey sites were described using two ordinations: 1. An ordination describing similarity between sites based on number and density of lichen species found at each site, termed lichen-site ordination; and 2. an ordination describing similarity between lichen species based on sites at which individual species were found and their frequency, termed lichen-species ordination. Both ordinations were based on data from NE-facing quadrats only.

For the lichen-site ordination, attributes of a site were the percentage frequencies of each lichen species at a site. Percentage frequency was defined as the number of quadrats at which a single lichen species was found, divided by the total number of quadrats for all species. This total was obtained by summing the numbers of quadrats at which each lichen species was found at that site.

For the lichen-species ordination, the lichen species themselves were the entities of the ordination. The attributes for this ordination were the occurrences (%) of any lichen species defined as the number of quadrats in which the species was found at a given site, divided by the number of quadrats in which the species was found at all sites.

Changes in Lichen Communities Between 1974 and 1978

In order to document general changes in lichen communities between 1974 and 1978, lichen samples were compared using two independent measures of similarity, namely, the Sorenson index (1948) and the chi-square test of association. These similarity measures were used to evaluate changes at individual sites and for individual species.

Statistical Procedures--

The Sorenson index often is used to estimate similarities between plant or animal communities. In this study, the index was used to estimate changes in lichen communities between the surveys. A high Sorenson-index value represents little change, and a low value represents a large change.

The Sorenson index was calculated for occurrence and frequency of lichen species at a site. It was determined by the formula $2w/(a + b)$, where a and b were the sums of values for the lichen species at the 1974 and 1978 surveys and w is the sum of the smaller of the a or b values (if a species did not occur at one or either of the sites, the index value was 0). The Sorenson index is a valuable measure of change because comparisons can be made between factors with small changes and between factors with large changes. A weakness of the Sorenson index for evaluation of change is that no statistical significance can be assigned to individual Sorenson-index values.

The chi-square test (Rx2) of association was used to provide a measure of the statistical significance of changes in lichen communities between 1974 and 1978. This test is a standard method for determining the independence of two frequency distributions. Following the recommendations of Snedecor and Cochran (1967), species frequencies were combined when necessary so that no expected frequencies were < 1.

For Individual Sites--

Changes at individual survey sites between 1974 and 1978 were evaluated using the Sorenson index and the chi-square test. These changes were determined for the NE-facing quadrats to obtain an estimate of general changes in lichen communities. For the Sorenson index $[2w/(a + b)]$, a and b were the sums of the numbers of quadrats in which each lichen species was found at that site for 1974 and 1978, respectively, and w was the sum of the smaller number of quadrats recorded for each lichen species in either of the two years. For the chi-square test, the differences in the numbers of quadrats containing all of the lichen species at a site were compared for each of the two years.

For All Sites--

Changes in distribution of individual species at all sites from 1974 to 1978 were evaluated using the Sorenson index and the chi-square test. Numbers of NE-facing quadrats in which a single species was found for the two surveys were used for both comparisons. For the Sorenson index, a and b were the sum of numbers of quadrats in which a single lichen species was found at all the survey sites in 1974 and 1978, respectively, while w was the sum of the smaller number of quadrats at each site in which that species was found in 1974 or 1978. For the chi-square test, the distribution among all sites of the number of quadrats for each species was compared between the two years.

For Quadrats Sampled on Different Sides of Trees--

Lichen communities of quadrats facing NE were compared with those of quadrats facing the generating station using the Sorenson index and chi-square test to estimate changes from 1974 to 1978 using the same procedures used to determine general changes in lichen communities. Since only NE-facing quadrats were sampled at sites 30, 31, and 32, these sites were not included in the quadrat comparisons. Sorenson index values and chi-square test results were calculated for quadrats facing the generating station, and the estimates of changes between 1974 and 1978 were compared with previously-calculated values for NE-facing quadrats. Comparisons were made for changes in distribution of lichen species at individual sites and for changes in individual lichen species at all sites.

For Sites Receiving Different Concentrations of SO_2—

Lichens in areas where emissions from the generating station were predicted to increase SO_2 levels 2 to 4 $\mu g/m^3$ over background levels (annual average) were compared with lichens in areas where emissions from the station were predicted to increase SO_2 levels < 2 $\mu g/m^3$ over background levels. The areas predicted to receive the higher and lower quantities of SO_2 from the generating station were determined from a model of 1976 stack emissions (Ragland and Goodell, in press). Lichen survey sites 1, 2, 7, 8, 9, 13, 14, 19, 20, 30, and 31 were grouped as higher concentration SO_2 sites because they are in areas estimated by the model to receive an annual average of 2 to 4 $\mu g/m^3$ SO_2 (0.0008 to 0.0016 ppm) over background levels (Figure 8). Sites 3 to 5, 10 to 12, 15 to 17, 21 to 23, 25 to 29, and 32 were grouped as lower concentration SO_2 sites, receiving an estimated annual average of < 2 $\mu g/m^3$ SO_2 (<0.0008 ppm) over background levels. Four sites have operated in the higher SO_2 area (3, 4, 8, and 9), while two sites operated in the lower SO_2 area (5 and 10) (Figure 8). The average SO_2 level monitored during the summer of 1977 at the higher concentration SO_2 sites averaged 6.3 $\mu g/m^3$ while at the lower concentration SO_2 sites the level was 5.1 $\mu g/m^3$ (corrected data in Table 10). There was considerable variation in average SO_2 levels at the sites because background levels varied significantly as seen in the data for 1974 to 1975 (Table 4). The average number of days per month with SO_2 fumigations from the generating stations was 2.1 for the higher concentration SO_2 monitoring sites and 1.3 for the lower concentration SO_2 monitoring sites (Table 8). The average number of summer hours during 1976 and 1977 with SO_2 levels above 120 $\mu g/m^3$ was 13.4 for higher concentration SO_2 sites and 7.7 for lower concentration SO_2 sites (Table 6). Differences between lichen communities in areas predicted to receive higher or lower SO_2 increments from the generating station were evaluated by comparing differences in distribution of all lichen species at individual sites in the two areas and by comparing differences in distribution of individual common lichen species at all sites in the two areas.

Evaluation of differences in distribution of all species between sites in higher- and lower-concentration SO_2 areas was accomplished for the groupings listed above. The previously-calculated 1974 to 1978 Sorenson index and chi-square-test values for lichen species at each site using data from NE-facing quadrats were compared between the two groups of sites. Sorenson-index values for the higher- and lower-concentration SO_2 sites were ranked separately; the combined ranks of site values for each of the two groups were compared using the Mann-Whitney test (Snedecor and Cochran 1967).

Air Pollution in Micrograms per Cubic Meter
1976 Annual Average

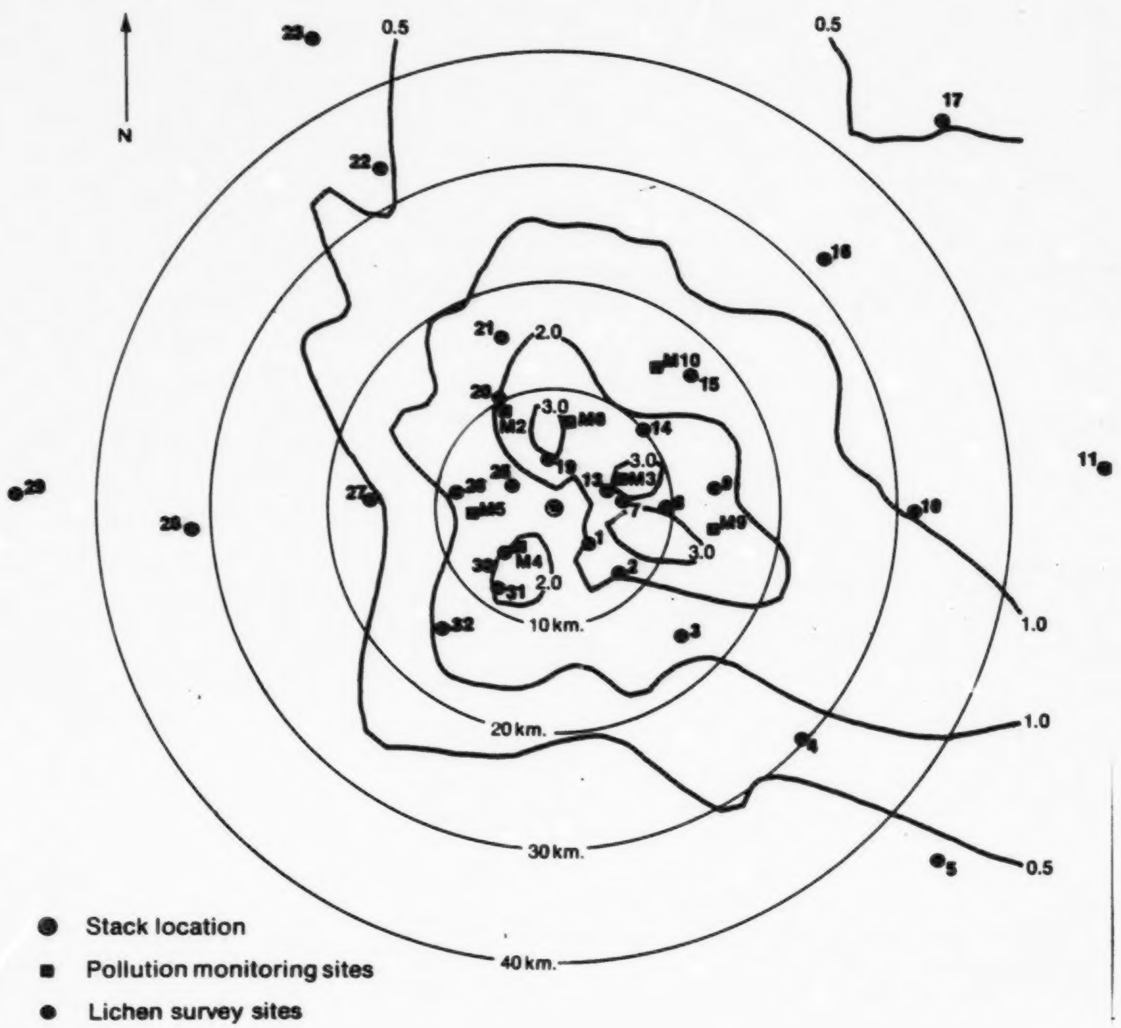

N
0.5
0.5
1.0
1.0
0.5
2.0
3.0
3.0
3.0
2.0
10 km.
20 km.
30 km.
40 km.
17
18
21
22
11
10
M10
15
14
M2
M3
M4
M5
M9
13
1
2
3
4
5
7
27
31
32
Stack location
Pollution monitoring sites
Lichen survey sites

Figure 8. Lichen site locations around the Columbia Generating Station and isopleths of predicted ground level SO_2 ($\mu g/m^3$) as a result of generating station operations.

Possible differences in the extent of changes between 1974 and 1978 between higher- and lower-concentration SO_2 sites also were investigated by comparing chi-square values for the two groups.

Differences in the distribution of common lichen species between higher- and lower-concentration SO_2 sites were investigated by comparing changes in distribution of common lichen species at higher concentration SO_2 sites with changes in the same species at lower concentration SO_2 sites between 1974 and 1978. Twenty-one relatively common lichen species were selected for these comparisons; 20 of these were the species found in NE-facing quadrats in at least 10 sites in 1974 and 1978. One species was found in NE-facing quadrats in only seven sites in 1978, but this species showed evidence of significant changes in distribution between 1974 and 1978. For each of the selected species, the number of NE-facing quadrats in which each species was present at each survey site in 1974 and 1978 were compiled separately for higher- and lower-concentration SO_2 sites. Sorenson-index values as detailed below were calculated for each species between 1974 and 1978 for the higher- and lower-concentration SO_2 groups separately. Data used for calculating index values were the number of quadrats at each site in 1 yr for each species divided by the number of quadrats at all sites in that year and group for each species (% occurrence). Occurrence, as calculated for Sorenson-index values in this comparison, represent differences in relative distribution of a lichen species at different sites and do not indicate increases or decreases in total number of quadrats at particular sites or over a group of sites.

For each species the possibility of significant differences in total numbers of quadrats between higher- and lower-concentration SO_2 sites were tested using a chi-square test of association. The total number of quadrats at which each species was found in 1974 and 1978 at each of the higher concentration SO_2 sites was compared with those for each of the lower concentration SO_2 sites.

Growth Anomalies on Particular Lichen Species

The presence of growth anomalies in selected lichen species was compared for sites located in areas predicted to receive higher or lower amounts of SO_2 from the station. The number of quadrats at which these alterations were noted from sites in the higher- and lower-concentration SO_2 groups were compared using chi-square tests of association. In these comparisons the proportion of quadrats at higher concentration SO_2 sites in which a growth anomaly occurred was compared with the corresponding proportion at lower concentration SO_2 sites.

RESULTS AND DISCUSSION

Description of Tree Communities

Importance values calculated for each tree species at each site in 1974 demonstrate the predominance of oak species (*Quercus* sp.) at most sites (Table 19). At all sites except sites 5, 12, 27, 29, and 30, oak species accounted for > 50% of the importance value of all species at the site.

Five oak species were encountered in the study: black oak (*Q. velutina*), red oak (*Q. borealis*), Hill's oak (*Q. ellipsoidalis*), white oak (*Q. alba*), and bur oak (*Q. macrocarpa*); black and white oak were the two most common oak species. Other tree species with importance values of > 20% at one or more sites were black cherry (*Prunus serotina*) at sites 1 and 11, black locust (*Robinia pseudo-acacia*) at site 5, white ash (*Fraxinus americana*) and basswood (*Tilia americana*) at site 12, and sugar maple (*Acer saccharum*) at sites 27 and 28. Number of tree species per site ranged from 1 at site 25 and 2 at site 31 to 10 each at sites 5 and 29. Detailed data for the tree-species surveys at each site are included in Appendix C.

The calculated importance values (Table 19) were used as the attributes for the site ordination based on the tree species shown in Figure 9 and Figure 10. These figures show the relationships of sites on planes defined by the X- and Y-ordination axes and by the X- and Z-axes, respectively. The most important attributes determining relative similarity of the survey sites were the importance values of black oak species. The separation of sites on the X ordination axis corresponds primarily to site values for two attributes, black oak- and red oak-importance values. To illustrate this pattern, three separate groups of black oak sites found along the X axis are circled on Figure 9 and Figure 10. At eight sites (7, 9, 10, 19, 20, 23, 25, and 32) black oak had an importance value of > 60%. At six sites (8, 14, 16, 21, 22, and 26) black oak importance values were 40% to 60%. At nine sites (1, 2, 3, 4, 5, 11, 15, 28, and 29), black oak had importance values between 15 and 40%. At six sites (12, 13, 17, 27, 30, and 31) no black oaks were present large numbers of red oaks or Hill's oaks were present. The four sites at which red oaks were found are 12, 17, 27, and 30. The two sites, (13 and 31) at which Hill's oak were found were clearly separated from all other sites along the Y axis. Site arrangement on the Z axis primarily represents differences among sites in the relative importance of white oak. Sites with high white oak importance values are toward the bottom of the Z axis (Figure 10), while sites with low white oak importance values are at the top of the Z axis.

The survey sites represent almost the full range of variation in oak forests and about 67% of the total variation in upland forests in southern Wisconsin, with CI values ranging from 100 to 675 (Table 19). The continuum of upland-forest composition in this area runs from very dry oak savannah or forest (bur-, black-, or Hill's oak) with a Wisconsin CI of 100 to 250 (Table 19) to maple-basswood forest growing in moist, deep soil areas, with CI of 800 to 1,000 (Curtis and McIntosh 1951, Bray and Curtis 1957, Curtis 1959).

Description of Lichen Communities

Lichens (48 species) were identified from samples of black oak bark (Table 20). In 1974, 42 species were identified and 46 in 1978. Two species (28 and 47) found in 1974 were not found in 1978, and six species (10, 13, 34, 37, 40, and 43) not found in 1974 were found in 1978. Of the 48 lichen species, 25 were foliose (leafy, flat), 18 were crustose (embedded in their substrate), and 5 were fruticose (erect, branching attached only at base). Size of lichen thalli ranged from only a few millimeters to several

TABLE 19. IMPORTANCE VALUES FOR TREE SPECIES* AND CONTINUUM-INDEX VALUES† FOR ALL LICHEN-SAMPLING SITES

Tree species	CAV‡	Site numbers									
		1	2	3	4	5	7	8	9	10	11
Acer rubrum	7.0	--	13.0	--	7.6	--	--	--	2.8	--	--
Acer saccharinum	4.0	--	--	--	--	6.5	--	--	--	--	--
Acer saccharum	10.0	--	--	--	--	--	--	--	--	--	--
Betula papyrifera	5.0	--	--	--	--	--	--	--	--	--	--
Carya cordiformis	8.5	--	--	--	--	--	--	--	--	--	--
Carya ovata	4.5	3.0	--	--	--	--	--	4.9	--	--	--
Celtis occidentalis	8.0	--	--	--	--	4.0	--	--	--	--	--
Fraxinus americana	6.5	--	--	--	--	2.3	--	--	--	--	--
Juniperus virginianum	1.0	--	--	--	--	--	--	--	--	--	--
Ostrya virginiana	8.5	--	--	--	--	--	--	--	--	--	--
Pinus resinosa	3.0	--	--	--	--	--	--	--	--	--	--
Pinus strobus	5.0	--	--	--	--	--	--	--	--	--	--
Populus grandidentata	4.5	--	--	--	--	--	--	--	7.6	--	2.3
Prunus serotina	3.5	29.1	11.5	6.7	3.3	1.3	--	11.4	9.4	2.5	38.7
Quercus alba	3.5	19.9	38.8	58.0	42.6	14.4	9.2	31.5	19.5	10.9	28.7
Quercus ellipsoidalis	1.0	--	--	--	--	--	--	--	--	--	--
Quercus macrocarpa	1.0	29.4	4.4	3.5	--	1.2	16.9	--	--	--	5.5
Quercus borealis	5.5	--	--	--	--	--	--	--	--	--	--
Quercus velutina	2.5	18.6	32.3	31.8	30.0	22.4	73.9	44.5	68.4	76.9	24.7
Robinia pseudoacacia	1.0	--	--	--	--	31.2	--	--	--	--	--
Tilia americana	7.5	--	--	--	--	1.4	--	--	--	9.5	--
Ulmus americana	7.5	--	--	--	16.6	3.7	--	--	--	--	--
Continuum index		261	352	309	422	247	234	318	292	310	314

*Importance value is (percentage density + percentage frequency + percentage dominance)/3. See text for explanation.

†Continuum-index value = sum of importance values x CAV for each tree species at a survey site.

‡CAV = Climax Adaptation Value = Wisconsin habitat preference index as established by Curtis (1959).

TABLE 19. CONTINUED

Tree species	Site numbers									
	12	13	14	15	16	17	19	20	21	22
Acer rubrum	--	--	--	--	--	--	--	--	--	--
Acer saccharinum	--	--	2.7	--	--	--	--	--	--	--
Acer saccharum	--	--	--	--	--	--	--	--	--	4.8
Betula papyrifera	--	--	--	--	--	6.5	--	--	--	--
Carya cordiformis	--	--	--	--	--	--	--	--	--	--
Carya ovata	3.4	--	--	10.0	--	4.1	--	--	--	--
Celtis occidentalis	--	--	--	--	--	--	--	--	--	--
Fraxinus americana	28.6	--	--	--	--	--	--	--	--	--
Juniperus virginianum	--	--	--	--	3.3	2.4	--	--	--	--
Ostrya virginiana	10.5	--	--	--	--	--	--	--	--	--
Pinus resinosa	--	--	--	--	--	--	--	--	--	--
Pinus strobus	--	--	--	--	1.6	--	--	--	--	--
Populus grandidentata	--	--	3.3	--	--	--	--	--	--	--
Prunus serotina	18.5	--	7.4	4.2	--	--	2.5	2.3	--	15.6
Quercus alba	6.6	53.0	35.8	32.9	21.8	15.6	20.4	10.9	52.2	21.8
Quercus ellipsoidalis	--	44.5	--	--	--	--	--	--	--	--
Quercus macrocarpa	--	2.5	--	5.3	13.9	--	--	2.8	--	--
Quercus borealis	10.1	--	--	--	--	71.4	--	--	--	--
Quercus velutina	--	--	50.8	34.5	59.3	--	77.1	81.9	47.8	50.2
Robinia pseudoacacia	--	--	--	--	--	--	--	2.2	--	--
Tilia americana	21.2	--	--	--	--	--	--	--	--	--
Ulmus americana	5.1	--	--	13.1	--	--	--	--	--	7.6
Continuum index	650	223	304	365	250	501	273	256	302	361

TABLE 19. CONTINUED

Tree species	Site numbers 23	25	26	27	28	29	30	31	32
Acer rubrum	--	--	7.4	--	--	14.7	--	--	--
Acer saccharinum	--	--	--	--	--	--	--	--	--
Acer saccharum	--	--	--	26.5	35.1	2.5	17.1	--	--
Betula paprifera	--	--	--	--	--	--	2.3	--	--
Carya cordiformis	--	--	--	5.8	--	--	--	--	--
Carya ovata	--	--	3.2	--	--	15.1	--	--	--
Celtis occidentalis	--	--	--	--	--	--	--	--	--
Fraxinus americana	--	--	--	--	--	--	--	--	--
Juniperus virginianum	--	--	--	--	--	--	--	--	--
Ostrya virginiana	--	--	--	--	--	2.4	6.2	--	--
Pinus resinosa	--	--	--	--	--	--	13.1	--	--
Pinus strobus	--	--	--	--	--	--	--	--	--
Populus grandidentata	--	--	--	5.8	3.4	--	--	--	--
Prunus serotina	--	--	--	3.7	9.8	5.8	10.3	--	2.1
Quercus alba	21.2	--	37.9	11.1	21.7	12.5	17.1	--	8.4
Quercus ellipsoidalis	--	--	--	--	--	--	--	96.2	--
Quercus macrocarpa	--	--	--	--	1.3	3.1	--	3.8	2.4
Quercus borealis	--	--	--	35.0	--	--	28.4	--	--
Quercus velutina	78.8	100.0	46.1	--	25.9	28.7	--	--	87.2
Robinia pseudoacacia	--	--	--	--	1.5	--	--	--	--
Tilia americana	--	--	3.9	5.5	--	2.7	2.9	--	--
Ulmus americana	--	--	1.5	6.5	4.5	13.0	2.7	--	--
Continuum index	271	250	354	675	578	478	568	100	257

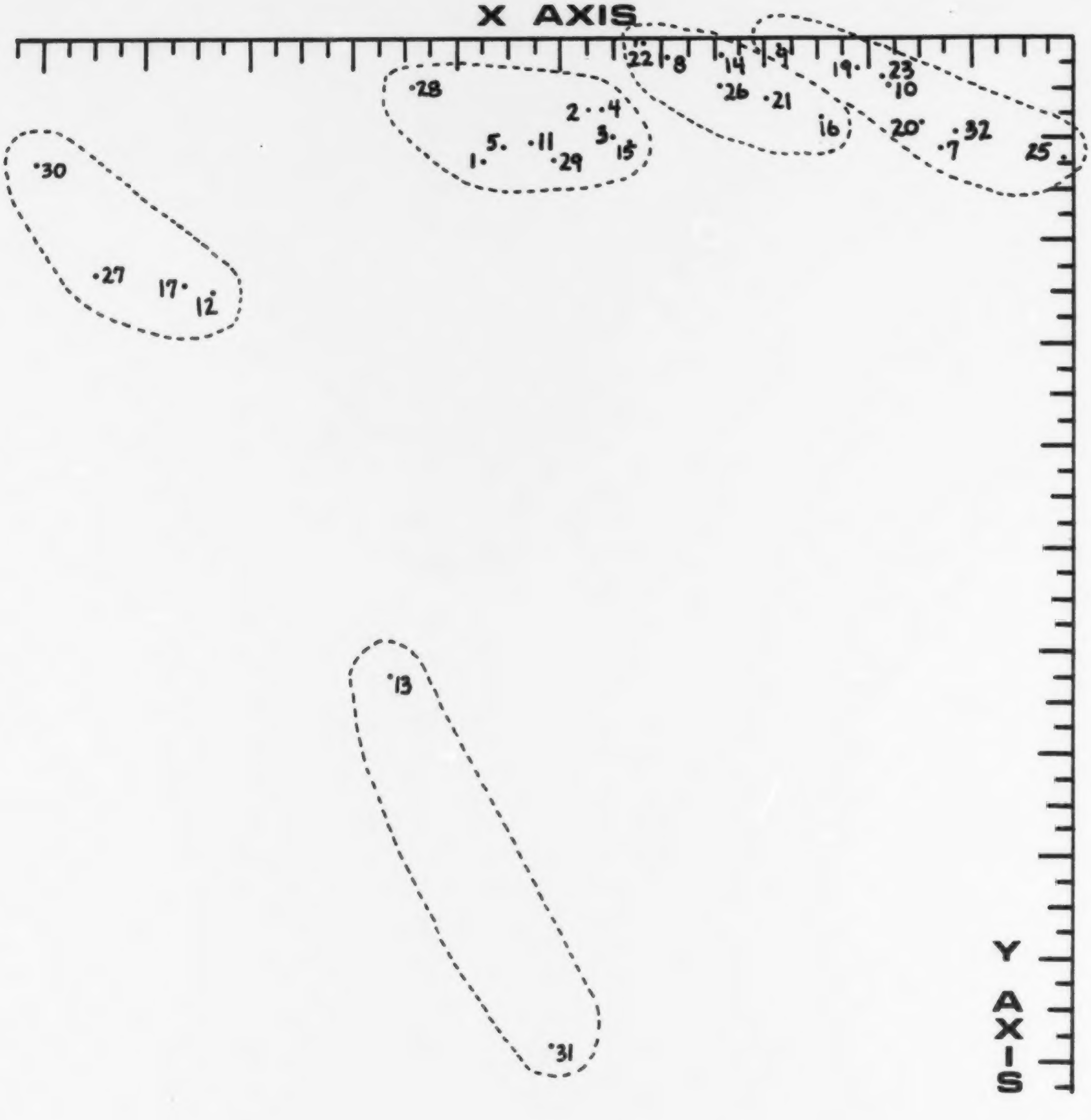


Figure 9. XY projection of site ordination of tree species importance values. Dotted lines enclose groups of sites with similar black oak group importance values as described in text. Sites tend to be arranged along the X-axis largely according to black oak and red oak importance values and along the Y-axis according to the Hill's oak importance value.

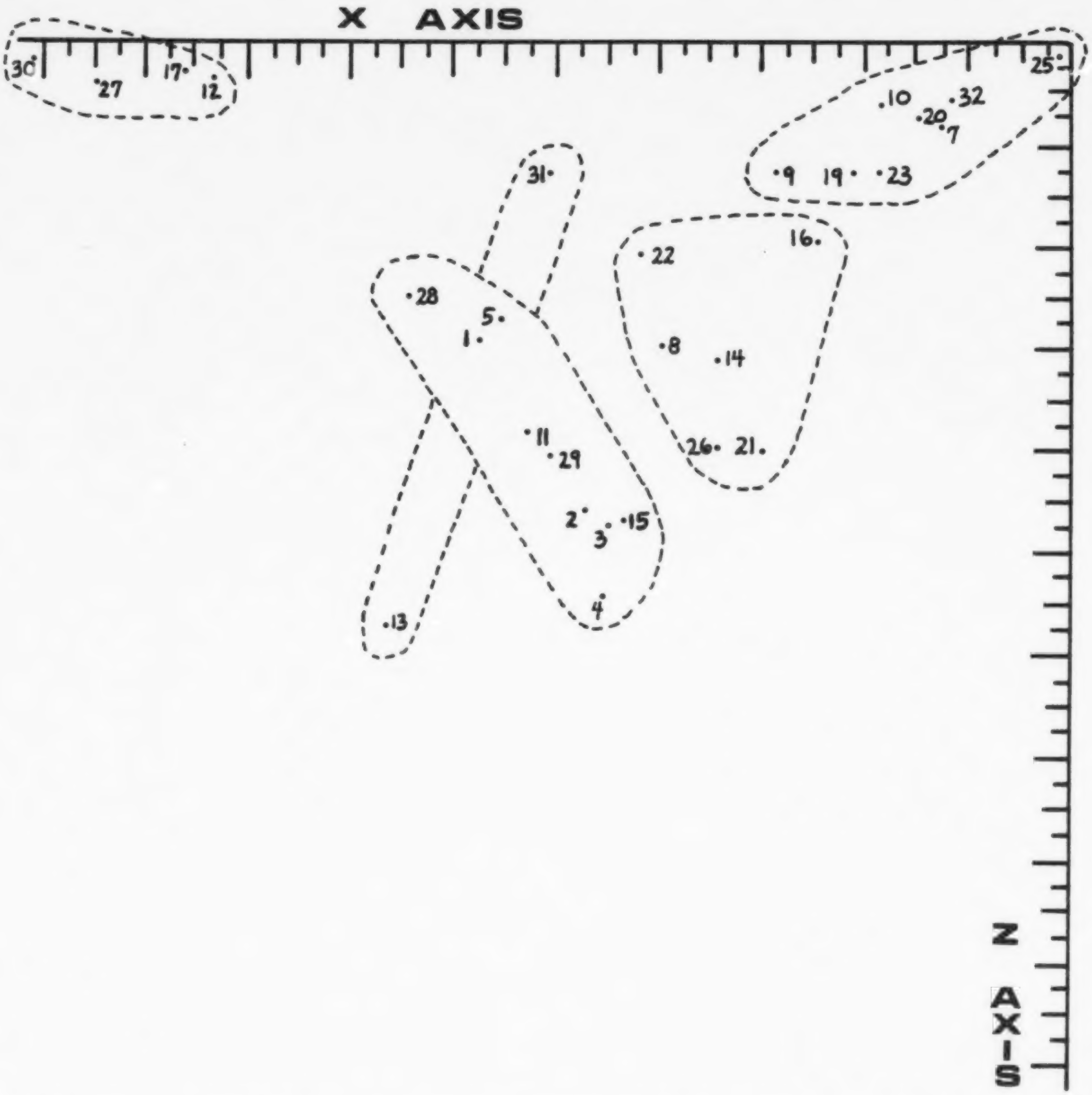


Figure 10. XZ projection of site ordination on tree species importance values. Dotted lines enclose groups of sites with similar black oak group importance values as described in text. Sites are distributed along the X-axis largely according to black oak group importance value and along the Z-axis according to the white oak importance value.

TABLE 20. LICHEN SPECIES IDENTIFIED FROM SAMPLES OF BLACK OAK BARK TAKEN FROM SITES NEAR THE COLUMBIA GENERATING STATION

Species number	Species	Growth form*
1	*Arthonia caesia* (Flot.) Körb	cr
2	*Bacidea chlorantha* (Tuck.) Fink	cr
3	*B. chlorococca* (Graewe ex. Stizenb.) Lett.	cr
4	*Buellia punctata* (Hoffm.) Mass.	cr
5	*B. schaereri* DeNot.	cr
6	*Caloplaca discolor* (Will.) Fink	cr
7	*Candelaria concolor* (Dicks.) Stein	f
8	*C. concolor* var. *effusa* (Tuck.) Burnh.	f
9	*Candelariella xanthostigma* (Ach.) Lett.	cr
10†	*Cladonia coniocraea* (Flörke) Spreng.	fr
11	*Evernia mesomorpha* Nyl.	fr
12	*Graphis scripta* (L.) Ach.	cr
13†	*Heterodermia tremulans* (Müll. Arg.) W. Culb.	f
14	*Lecanora conizaea* (Ach.) Nyl.	cr
15	*L. hypoptoides* Nyl.	cr
16	*L.* unidentified sp. Brodo	cr
17	*L. varia* (Ehrh.) Ach.	cr
18	*Lepraria membranacea* (Dicks.) Vain.	cr
19	*L. neglecta* (Nyl.) Lett.	cr
20	*Opegrapha pulicaris* (Hoffm.) Schnal.	cr
21	*Parmelia aurulenta* Tuck.	f
22	*P. bolliana* Mull. Arg.	f
23	*P. caperata* (L.) Ach.	f
24	*P. flaventior* Stirt.	f
25	*P. galbina* Ach.	f
26	*P. rudecta* Ach.	f
27‡	*P. saxatilis* (L.) Ach.	f
28†	*P. squarrosa* Hale	f
29	*P. subaurifera* Nyl.	f
30	*P. sulcata* Tayl.	f
31	*P. ulophyllodes* (Vain.) Sav.	f
32	*Pertusaria pustulata* (Ach.) Duby	cr
33	*Physcia aipolia* (Ehrh.) Hampe	f
34†	*Physconia grisea* (Lam.) Poelt	f
35	*Physcia millegrana* Degel.	f
36	*P. orbicularis* (Neck.) Poetsch.	f
37†	*P. orbicularis f. albociliata* (Bouly de Lesd.) Thoms.	f
38	*P. orbicularis f. rubropulchra* (Neck.) Poetsch.	f
39	*P. stellaris* (L.) Nyl.	f
40†	*Physciopsis adglutinata* (Flk.) Choisy	f
41	*P. syncolla* (Tuck. ex. Nyl.) Poelt	f
42	*Pyrenula neglecta* Harris	cr
43	*Pyxine sorediata* (Ach.) Mont.	f
44	*Ramalina fastigiata* (Pers.) Ach.	fr
45	*R. sinensis* Jatta	fr
46	*Rinodina papillata* Magn.	cr
47‡	*Usnea hirta* (L.) Wigg.	fr
48	*Xanthoria fallax* (Hepp.) Arn.	f

*cr is crustose, f is foliose, fr is fruticose.
†These species were found only in 1978.
‡These species were found only in 1974.

centimeters in diameter and large foliose lichens occasionally reached 10 cm in diameter.

The number of lichen species collected at any one site ranged from 16 at site 12 to 32 at sites 13 and 27. The number of species found in the quadrats facing NE was similar to the number found in the quadrats facing the generating station (Table 21, Table 22). Complete data for the number of quadrats in which each lichen species was found at each site in 1974 and 1978 are given in Appendix D.

Lichen Site Ordination--

The ordination of sites based on lichen species at each site is diagrammed in Figure 11 and Figure 12. The only separation of sites apparent on this ordination was related closely to the number of species found at each of the sites. The eight sites with the fewest species (sites 5, 7, 11, 12, 14, 17, 19, and 29) are all located at the top, bottom, and left fringes of the point cluster, leaving the average and relatively species-rich sites in the right-center portion of the point cluster. These species-poor sites are marked with triangles in Figure 11 and Figure 12. The five most species-rich sites (sites 1, 13, 22, 28, and 32) are marked with asterisks. The species-rich sites are loosely-clustered on the X- and Y-axes and more tightly- clustered on the Z-axis.

No groups of sites in a particular direction or area can be separated readily on the ordinations. No general differentiation of sites in an E-W or N-S direction in the lichen site ordination was apparent, nor was there any pattern of site location with respect to distance from the generating station.

This arrangement of sites based on lichen species is different from the ordination of sites based on tree species discussed previously (compare site locations in Figure 9, Figure 10 with those in Figure 11, Figure 12). Groups of sites, which were separated on the tree species ordination by the importance values of different black oak-group species (circled groups on Figure 9, Figure 10), are not separated on the lichen-site ordination, and the groups are not even recognizable. This result indicates that no relationship exists between tree-species composition at a site and composition of the bark-lichen community on black oaks at that site.

There are no groups of sites which are segregated in the lichen ordination because their lichen species composition is different from that of another group of sites. The more common lichen species at the survey sites are relatively common at all sites and the less common lichen species are uncommon at all sites.

Since the ordination showed that the major variation among the sites was not related to differences in lichen species composition, it has been assumed that the lichen samples represent variation within a single community type rather than several distinct communities. This finding is consistent with previous research on black oak lichen communities in southern Wisconsin (Hale 1955).

TABLE 21. NUMBER OF LICHEN SPECIES AT EACH SITE FOUND IN QUADRATS FACING NE FOR SURVEYS MADE AT EACH SITE IN 1974 AND 1978 AND COMPARISON INDICES FOR THE CHANGES IN LICHEN DISTRIBUTION BETWEEN 1974 AND 1978

				Comparison indices*	
Site number	Distance (km) and direction from generating station	Number of species		Sorenson index, 1974 to 1978	Chi-square index, 1974 to 1978
		1974	1978		
1	6.4 SE	19	18	0.62	NS
2	9.7 SE	18	20	0.72	NS
3	14.5 SE	17	24	0.74	NS
4	30.6 SE	15	15	0.72	NS
5	48.3 SE	10	11	0.79	NS
7	7.2 E	12	15	0.60	$p<0.05$
8	10.5 E	17	18	0.65	NS
9	14.5 E	17	19	0.53	NS
10	30.6 E	17	16	0.79	NS
11	48.3 E	12	14	0.76	NS
12	64.4 E	7	9	0.65	NS
13	4.8 NE	20	22	0.63	NS
14	8.9 NE	13	17	0.64	NS
15	15.3 NE	15	19	0.75	NS
16	33.0 NE	18	15	0.76	NS
17	51.5 NE	12	21	0.68	$p<0.05$
19	5.6 NNW	13	13	0.84	NS
20	9.7 NNW	17	24	0.67	NS
21	17.7 NNW	16	16	0.71	NS
22	33.0 NNW	28	26	0.67	NS
23	46.7 NNW	17	23	0.74	NS
25	4.0 W	16	20	0.77	NS
26	9.7 W	18	16	0.62	NS
27	14.5 W	17	18	0.79	NS
28	32.2 W	24	20	0.73	NS
29	46.7 W	13	16	0.70	NS
30	4.8 SW	18	15	0.63	$p<0.05$
31	9.7 SW	18	27	0.80	NS
32	16.1 SW	23	20	0.69	NS
Average		16.5	18.2		

*Comparison indices were calculated using number of quadrats per species for all species at a site, not number of species per site.

TABLE 22. NUMBER OF LICHEN SPECIES AT EACH SITE FOUND IN QUADRATS FACING THE GENERATING STATION FOR SURVEYS MADE AT EACH SITE IN 1974 AND 1978 AND COMPARISON INDICES FOR THE CHANGES IN LICHEN DISTRIBUTION BETWEEN 1974 AND 1978

Site number	Distance (km) and direction from generating station	Number of species		Comparison indices*	
		1974	1978	Sorenson index, 1974 to 1978	Chi to square index, 1974 to 1978
1	6.4 SE	19	23	0.67	NS
2	9.7 SE	20	22	0.70	NS
3	14.5 SE	16	17	0.68	NS
4	30.6 SE	15	14	0.69	NS
5	48.3 SE	12	15	0.64	NS
7	7.2 E	11	19	0.51	NS
8	10.5 E	17	18	0.75	NS
9	14.5 E	19	18	0.70	NS
10	30.6 E	11	12	0.70	NS
11	48.3 E	8	15	0.58	NS
12	64.4 E	7	10	0.73	NS
13	4.8 NE	16	18	0.75	NS
14	8.9 NE	15	15	0.69	NS
15	15.3 NE	14	13	0.85	NS
16	33.0 NE	14	13	0.81	NS
17	51.5 NE	14	17	0.70	NS
19	5.6 NNW	11	15	0.79	NS
20	9.7 NNW	19	20	0.77	NS
21	17.7 NNW	14	18	0.68	NS
22	33.0 NNW	16	19	0.70	NS
23	46.7 NNW	20	21	0.79	NS
25	4.0 W	20	19	0.79	NS
26	9.7 W	20	17	0.72	NS
27	14.5 W	15	16	0.75	NS
28	32.2 W	21	15	0.70	NS
29	46.7 W	14	17	0.74	NS
Average		15.3	16.8		

*Comparison indices were calculated using number of quadrats per species for all species at a site, not number of species per site.

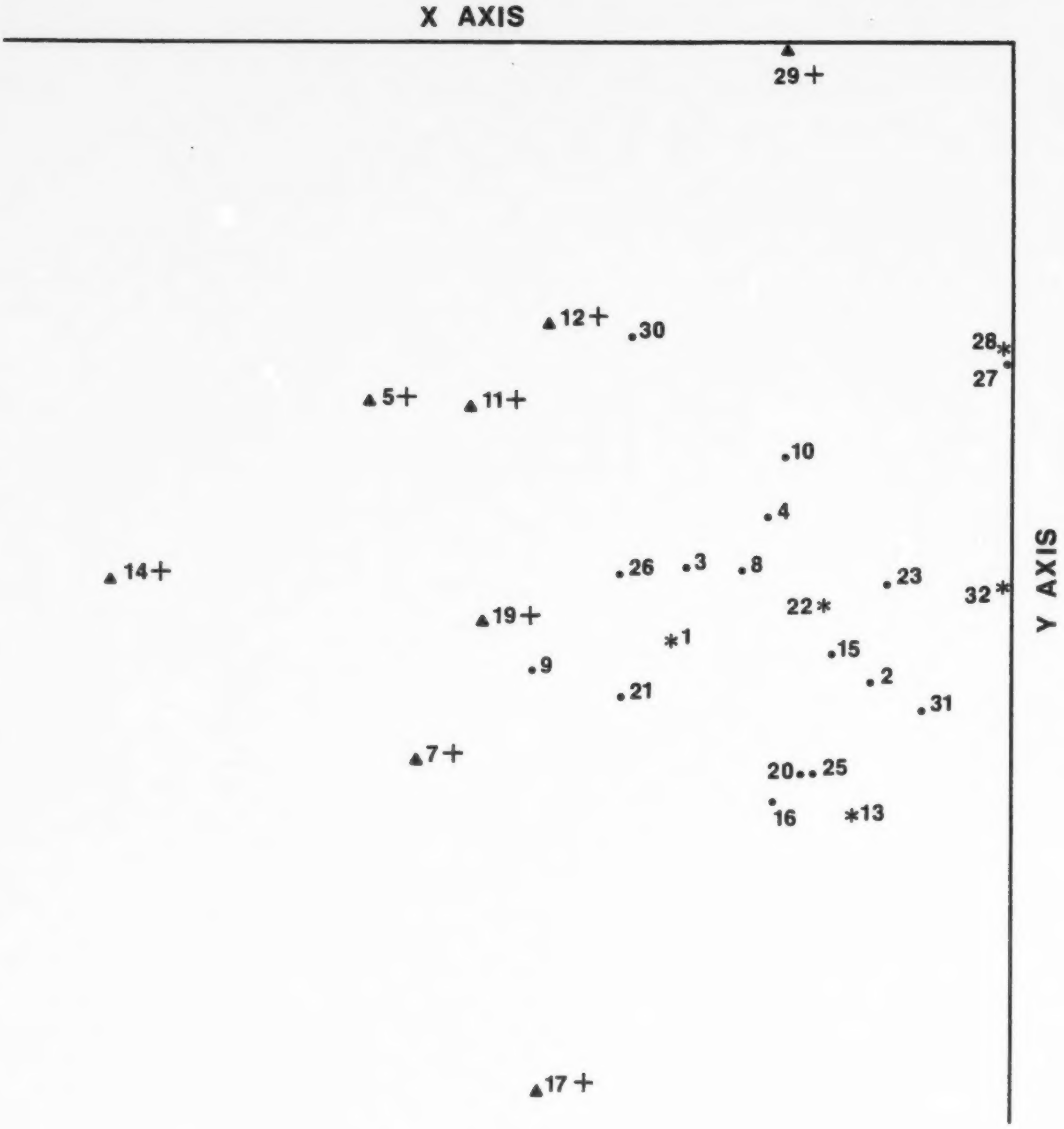


Figure 11. XY projection of site ordination on lichen species occurrence in NE-facing quadrats. Species-rich sites are found at right center, sites progressively poorer in species are found radiating in all other directions from that area of the ordination. Species-rich sites are marked with an asterisk, and species-poor sites are marked with a plus sign. (See definitions in text.)

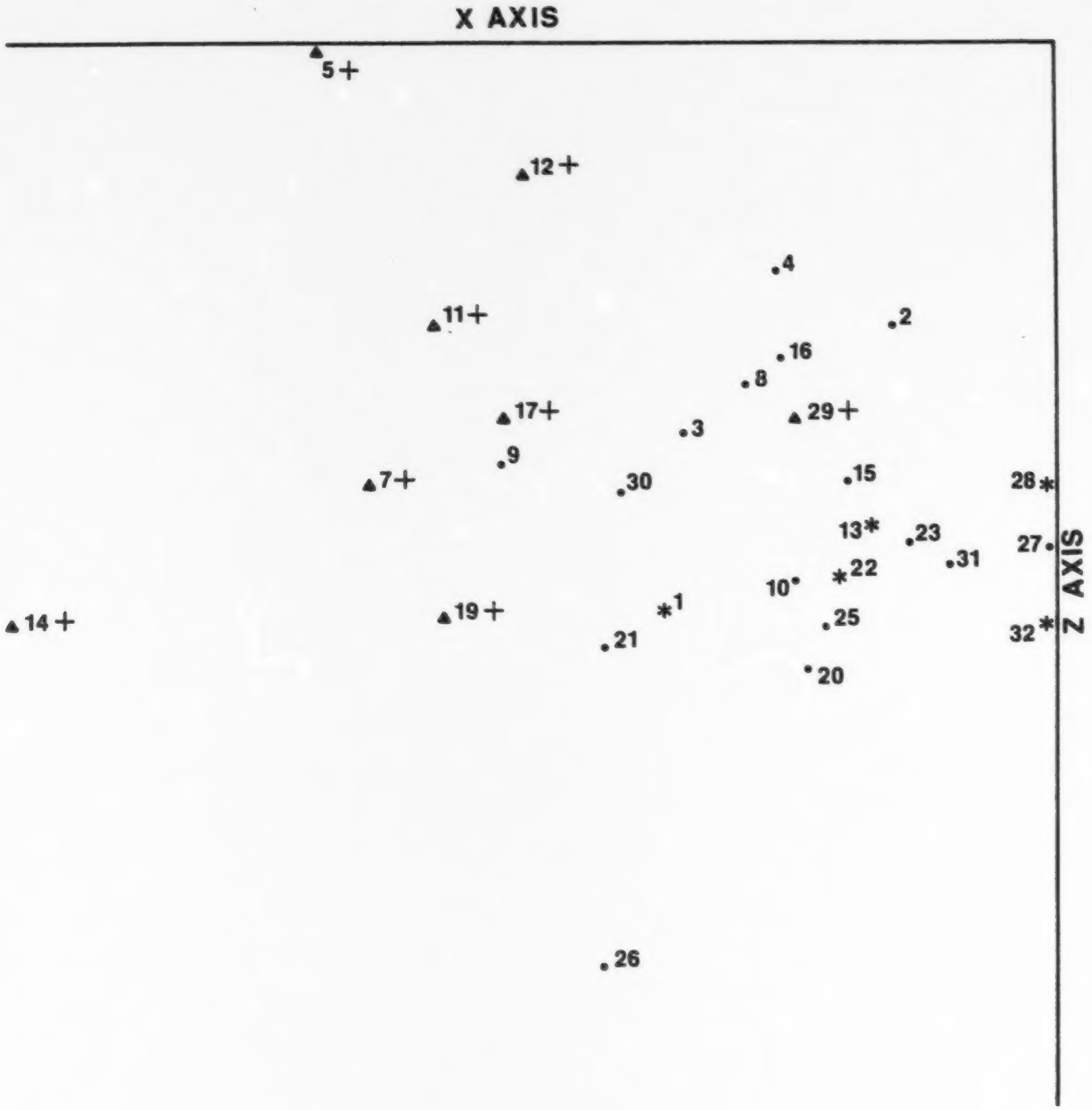


Figure 12. XZ projection of site ordination on lichen species occurrence in NE-facing quadrats. Species-rich sites are found at right center, sites progressively poorer in species are found radiating in all other directions from that area of the ordination. Species-rich sites are marked with an asterisk, and species-poor sites are marked with a plus sign. (See definitions in text.)

Lichen Species Ordination--

This ordination compared individual lichen species found in 1974 based on their presence at the same survey sites. The 42 lichen species are coded in Figure 13 and Figure 14 by the species numbers given in Table 20. The large group of lichens plotted in the lower left portion of the XY and XZ graphs represent those lichens that were found in largest numbers in the surveys.

The dissimilarity between lichen species that can be seen in the ordination diagrams (Figure 13, Figure 14) corresponds principally to the number of sites at which a particular species was found. To illustrate this correspondence, lichen species were divided into six groups and separated by dashed lines based on the number of sites at which each species was found (using only data from NE-facing quadrats). In 1974, three species (1, 20, and 35) were found in at least 26 survey sites; four (8, 16, 26, and 46) in 21 to 25 sites; nine (2, 21, 22, 23, 30, 32, 36, 38, and 42) in 16 to 20 sites; five (3, 12, 14, 18 and 39) in 11 to 15 sites; seven (4, 7, 9, 15, 17, 25, and 31) in 6 to 10 sites; and the other 14 species occurred in five or fewer sites. The clarity of the trend represented by these groups on the ordination is important: only two species (marked with asterisks) on the XY plane are displaced from other species in the particular abundance groups.

This ordination demonstrates that the relative commonality of species is important in determining similarity between species and illustrates the homogeneity of the lichen communities studied. The common lichen species--found at 90% or more of the available locations--inevitably were found at most of the sites. The moderately common to moderately uncommon species, those which were each found at 6 to 20 of the 29 sites, were not so constrained but were still close to one another on the ordination, showing that they generally were found at the same sites. The only species that were different from other species with respect to the sites at which they were found were the very uncommon species, i.e., those which were found at five or fewer sites.

There were several species separated on the upper half of the ordination of Figure 14 that were located primarily N of the generating station. These species are delineated by an arbitrary line drawn on Figure 14. Nine of the 12 species above this line were located primarily at sites N of the station; however, these species were all relatively uncommon species. Since no directional distribution of the relatively common species was indicated, this trend was not considered important in this study.

The lichen-species ordination demonstrates a result that was inferred from the lichen-site ordination: lichen species do not segregate into groups occurring at particular survey sites. Instead the common lichen species were found to be similar to one another based on the percentage of occurrence at survey sites, while the less common species differed greatly from one another in the ordination.

The lichen species ordination and the lichen site ordination have demonstrated that lichen communities from the survey sites constitute a

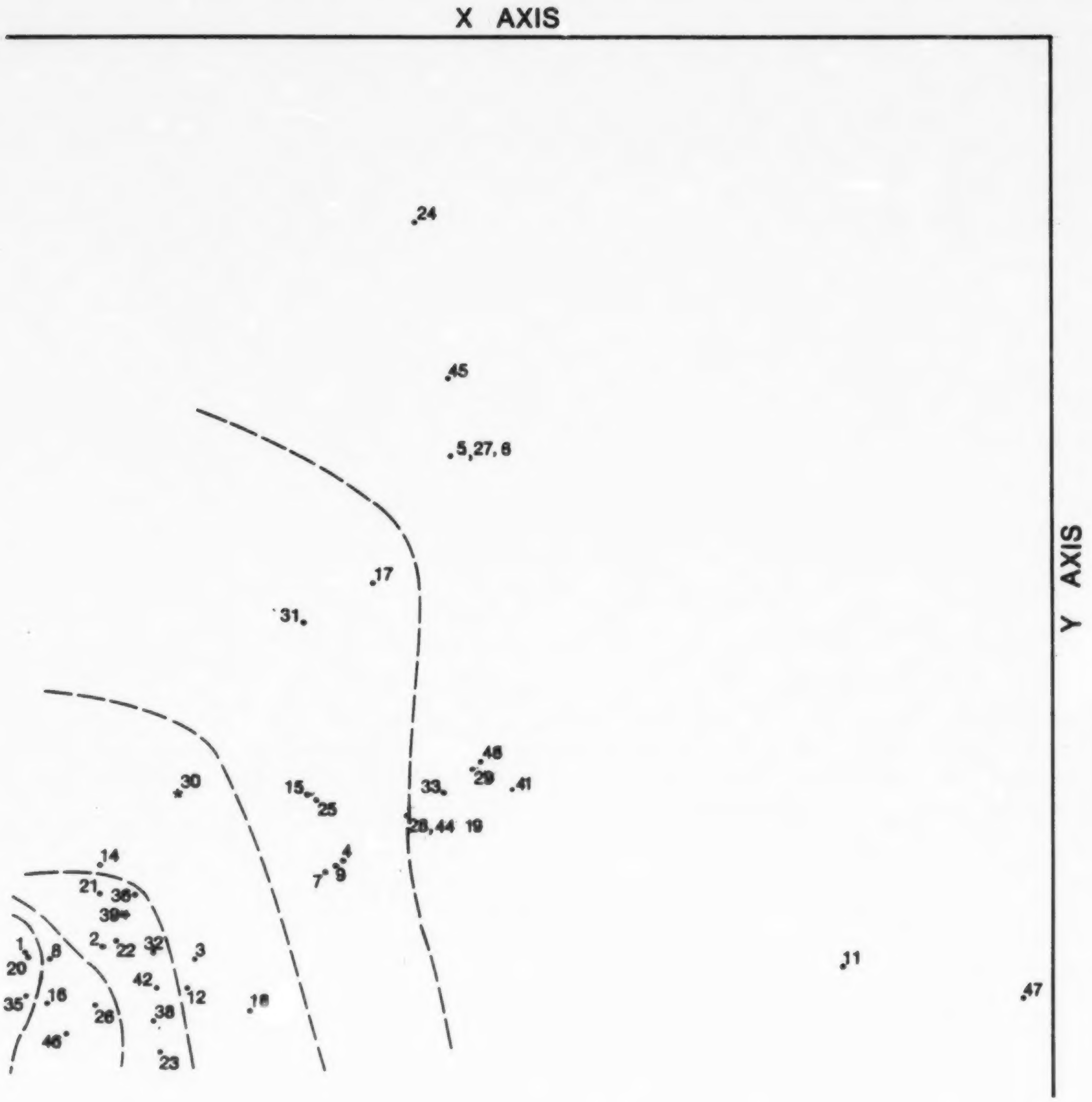


Figure 13. XY projection of lichen species ordination on occurrence by site in NE-facing quadrats. Dotted lines separate groups of common to uncommon lichen species with common species at lower left and uncommon species toward the upper right. Ordination numbers refer to lichen species as numbered in Table 20. The two lichen species marked by asterisks are out of their appropriate abundance group. (See text for explanation.)

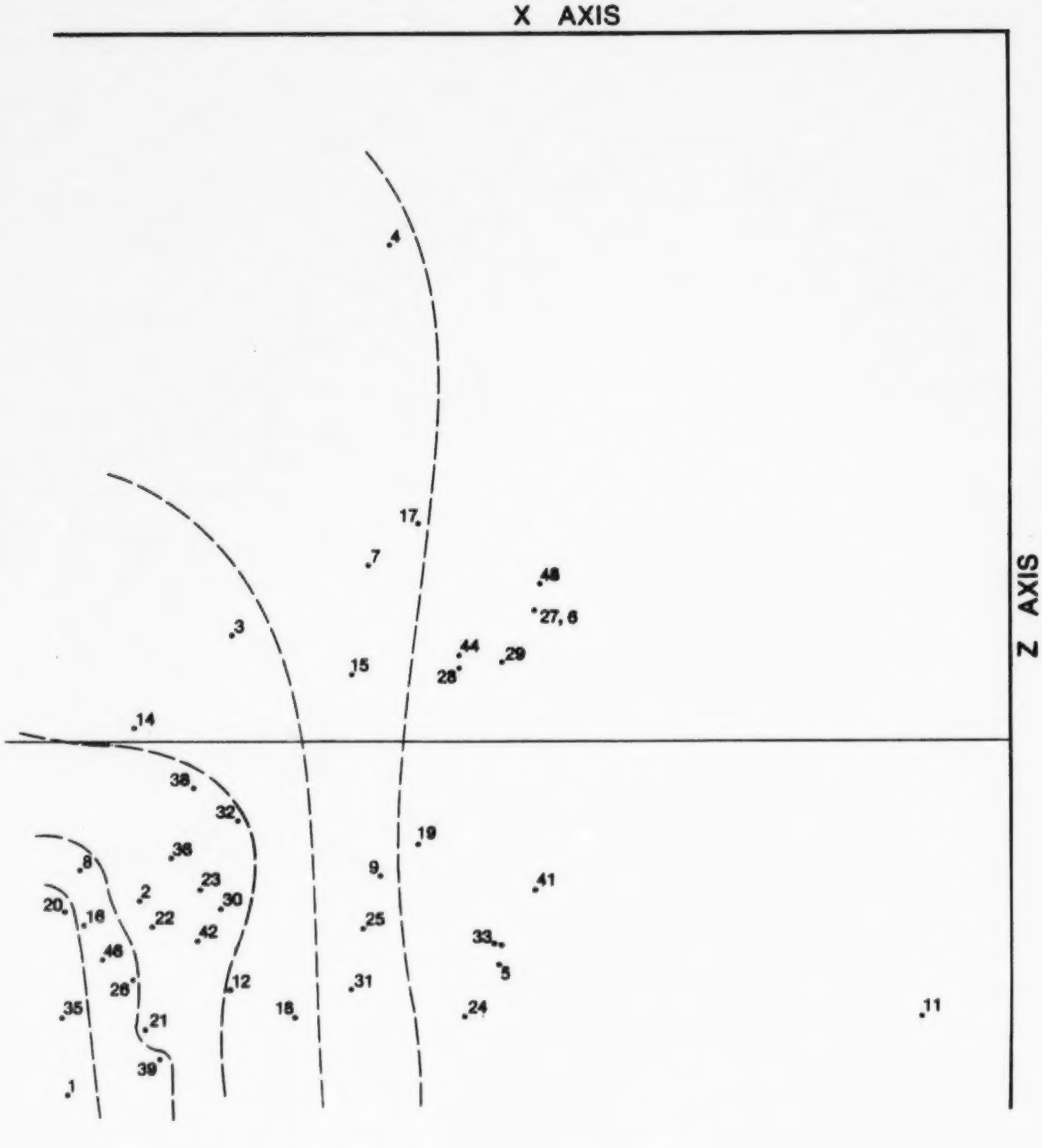


Figure 14. XZ projection of lichen species ordination on occurrence by site in NE-facing quadrats. Dotted lines separate groups of common and uncommon lichen species, with common species at lower left and uncommon species toward the upper right. Solid line separates more northern lichen species from others as described in text. Ordination numbers refer to lichen species as numbered in Table 20.

single fairly homogeneous group. It is therefore reasonable to assume that lichens at the sites are members of the same community. Natural changes in the lichen community between 1974 and 1978 could be expected to be similar over all sites, barring unusual disturbances at individual sites or at a group of sites.

Changes in Lichen Communities Between 1974 and 1978

During the 4 yr between the two lichen surveys, a minimum amount of change in the lichen communities at the survey sites was expected. Such changes could be caused by such factors as natural developmental changes in woods at individual sites, difference in climatic conditions, especially temperature and moisture, and severe storm damage or man-induced general changes in the area, e.g., removal of trees or construction in adjacent areas or an increase in background air pollution in southern Wisconsin. Small changes in lichen communities at individual sites could result from chance losses or introduction of uncommon species. In addition to real changes in lichen communities between 1974 and 1978, some differences between the two surveys are expected because of sampling errors or differences in the thoroughness with which lichen specimens were recognized.

Assessments of changes in lichen communities between 1974 and 1978 were made by examining the changes in lichen communities at individual survey sites and changes in individual lichen species over all sites.

For Individual Sites--

The average number of lichen species per site in NE-facing quadrats increased from 16.5 in 1974 to 18.2 in 1978 (Table 21). Although this increase is small, it was found to be significant by a paired t-test ($p < 0.025$). Of the 29 sites, 18 showed an increase in species number from 1974 to 1978, but no association was apparent between the locations of sites with respect to the station and their change in species number. These increases in species per site may represent a true increase in number of species of lichens, or may represent a more thorough examination of 1978 bark samples for very small lichen specimens.

The degree of change between 1974 and 1978 in the relative importance of lichen species at sites, as measured by the Sorenson index, ranged from 0.53 for site 9 to 0.84 for site 19 (Table 21); an increasing amount of change is represented by smaller index values. The high value of 0.84 recorded for site 19 indicates little change. With normal sampling error considered, a Sorenson index value of about 0.90 would be expected from two independent samples at the same site in the same year. These Sorenson-index values for the comparison of the same sites between 1974 and 1978 represent a narrower range of variation than was found for the Sorenson-index values for site pairs in 1974 calculated in the lichen-site ordination. Changes at sites over the 4-yr span of the study have been less than the original differences between sites in lichen species composition.

Since actual numbers of quadrats for each species were used to calculate the Sorenson index values in Table 21, they reflect not only the effects of proportional changes in lichen species at each site over the 4 yr, but also the effects of increases or decreases in the total number of observations for lichen species at each site when the proportional numbers are constant.

Differences between the 1974 and 1978 surveys at each site were measured by chi-square tests of association (Table 21). All the sites with significant or nearly significant chi-square values also had low Sorenson-index values. Only two sites (1 and 26) with very low Sorenson-index values had non-significant chi-square values. These comparisons suggested that in general the chi-square test and the Sorenson index measured similar changes at the sites. Since chi-square values measure only proportional differences between years, proportional changes appear to be the important changes.

For All Sites--

Evaluation of changes between 1974 and 1978 could not be made for all lichen species. Of the 48 species identified during the two surveys, two were never found in NE-facing quadrats and eight more were found in NE-facing quadrats in only one of the two sampling times. The remaining 38 species were evaluated for differences in numbers or distribution pattern over the 4-yr span. The number of sites at which a species was found varied widely (Table 23). Species 35 was found at all sites in both years while species 6 was found at only one site in each survey (not the same sites). The range in number of quadrats in which a species was found was even wider. Species 35 was found in 533 of a possible 580 quadrats at all sites in both years, but nine species (5, 6, 11, 19, 29, 33, 44, 45, and 48) were found in fewer than 20 quadrats over all 29 sites on each of the two sampling dates. Not much importance is attached to the presence or absence of these nine species from the sites because they were so uncommon.

Many species exhibited large changes in distribution between 1974 and 1978 as indicated by the low Sorenson-index values (Table 23). However, most of the low values resulted from sensitive species that were found on only 1 to 3 trees at each site (Appendix D). Three of the species (2, 3, and 18), all with low Sorenson-index values, were found to have changed significantly using the chi-square test. Chi-square values were not calculated for several species because expected values were too small for this test.

For Quadrats Sampled on Different Sides of Trees--

If air pollution from the generating station was affecting bark-lichen communities in the area, the effects might be greatest on the sides of trees facing the generating station. Comparison of the degree of change between 1974 and 1978 of lichens in NE-facing quadrats (Table 21) and of lichens facing the generating station (Table 22) suggest that little or no difference exists. Using the Sorenson index (Table 21, Table 22), no greater change between 1974 and 1978 was found for lichens in quadrats facing the station. In fact, lichens in NE-facing quadrats at about 60% of the sites changed more over the 4-yr period than lichens in quadrats facing the station; most of the significant chi-square values were in NE-facing

TABLE 23. NUMBER OF SITES FOUND TO HAVE EACH LICHEN SPECIES IN THE QUADRATS FACING NE FOR SURVEYS MADE IN 1974 AND 1978 AND COMPARISON INDICES FOR THE CHANGES IN LICHEN DISTRIBUTION BETWEEN 1974 AND 1978

Species number	Number of sites†		Comparison indices*	
	1974	1978	Sorenson index, 1974 to 1978	Chi-square value, 1974 to 1978
1	28	29	0.80	NS
2	18	17	0.44	$p<0.05$
3	12	15	0.33	$p<0.05$
4	7	8	0.59	NS
5	2	7	0.00	NS
6	1	1	0.00	--
7	7	9	0.54	NS
8	21	29	0.73	NS
9	7	5	0.40	NS
10	0	1	--	--
11	2	1	0.00	--
12	15	16	0.72	NS
13	0	1	--	--
14	15	13	0.44	NS
15	6	14	0.47	NS
16	23	21	0.76	NS
17	6	7	0.33	NS
18	15	8	0.30	$p<0.05$
19	5	3	0.15	NS
20	26	29	0.78	NS
21	20	23	0.65	NS
22	16	20	0.71	NS
23	20	22	0.74	NS
24	3	15	0.27	NS
25	10	8	0.37	NS
26	21	26	0.79	NS
27	0	3	--	--
28	4	0	--	--
29	2	3	0.44	NS
30	16	18	0.63	NS
31	6	5	0.50	NS
32	16	11	0.62	NS
33	2	1	0.00	--
34	Not found in northeast quadrats			
35	29	29	0.96	NS
36	17	20	0.69	NS
37	0	1	--	--
38	17	14	0.50	NS
39	21	19	0.63	NS
40	0	3	--	--
41	1	0	--	--
42	16	15	0.46	NS
43	Not found in northeast quadrats			
44	3	6	0.00	NS
45	2	1	0.00	--
46	22	22	0.76	NS
47	1	0	--	--
48	1	3	0.33	NS

*Comparison indices were calculated using number of quadrats per site at all sites for each species, not number of sites per species.

†29 sites sampled.

quadrats. Comparison of changes between 1974 and 1978 for individual lichen species based on NE-quadrat data (Table 23) with changes based on data from all quadrats produced similar conclusions. These findings indicate that if the generating station affected lichens at the survey sites, such effects must have occurred equally on all sides of the trees.

For Sites Receiving Different Concentrations of SO_2--

Before statistical comparisons were made between sites in the areas predicted to receive different levels of SO_2, certain baseline characteristics of the lichen communities were investigated to determine if the two groups of sites represented similar samples of lichen communities around the station. The two groups of sites in the predicted higher- and lower-concentration SO_2 areas appeared to be comparable with respect to density of lichen communities: three of 11 higher concentration SO_2 sites and five of 18 lower concentration SO_2 sites had fewer than 16 species in the two sampling years, while 3 higher concentration SO_2 sites had more than 20 species in the two sampling years (Table 21). In general, sites in the higher concentration SO_2 group appeared to be scattered at random in the 1974 lichen-site ordination (Figure 11, Figure 12), as were sites in the lower concentration SO_2 group. Within both groups the number of species per site increased slightly from 1974 to 1978.

Comparison of differences between 1974 and 1978 for higher- and lower-concentration SO_2 sites by calculation of Sorenson-index values (Table 21) showed that higher concentration SO_2 sites changed somewhat more (average Sorenson-index value is 0.67) than lower concentration SO_2 sites (average Sorenson-index value is 0.72). The differences in values between the two groups could not be tested for significance using standard parametric tests because Sorenson-index values are percentage values and not absolute numbers; a non-parametric test was used instead. The individual Sorenson-index values for each of the sites in the two groups were ranked, and the relative ranks of the values of the higher concentration SO_2 group were compared with the total of the two groups using the Mann-Whitney Test (Snedecor and Cochran 1967). The values for sites in the higher concentration SO_2 group ranked significantly lower ($p < 0.05$) than those for sites in the lower concentration SO_2 group. This result means that, as a group, lichen communities at higher concentration SO_2 sites changed more between 1974 and 1978 than did lichen communities at lower concentration SO_2 sites. The significant difference resulted apparently from a change in the proportion of particular lichen species at each site rather than total numbers of lichens at each site.

Comparison of changes between 1974 and 1978 at higher concentration SO_2 sites with those at lower concentration SO_2 sites using a chi-square test showed only three sites with significant change (Table 21). Two of these sites (7 and 30) were in areas predicted to receive higher SO_2 levels, and one site (17) was in the area predicted to receive lower SO_2 levels. One higher- and the lower-concentration SO_2 site gained in number of species identified while the other higher concentration SO_2 site declined in number of species.

The results of these two tests indicate that those sites predicted to receive more SO_2 from the station changed slightly more between 1974 and 1978 than did those sites expected to receive relatively less SO_2 from the station. These documented changes, however, involved increases in lichen species at certain sites and decreases in species at other sites in the higher- and lower-concentration SO_2 areas.

The 21 common lichen species chosen for comparisons between higher- and lower-concentration SO_2 areas (Table 24) include the species delineated by the four most common species groups in the lichen-species ordination (Figure 13, Figure 14). Results of evaluations of differences between 1974 and 1978 for these individual lichen species indicate that differences in total numbers of observations and percentage of occurrence of a species at survey sites were important for many species.

Changes in the percentage of occurrence of each of the selected lichen species over the 4-yr period ranged from great (Sorenson-index 0.09) to little (Sorenson-index 0.94), and some species showed differential changes between higher- and lower-concentration SO_2 sites. The low Sorenson-index values were associated with species observed infrequently over the sites and hence were often present in one year but not in another. The L-H column of Table 24 summarizes differences between site groups for each species. Nine species changed about the same at higher- and lower-concencentration SO_2 sites (the magnitude of $L\text{-}H < 0.10$), while eight species changed more and four species changed less at higher- than at lower-concentration SO_2 sites ($L\text{-}H > 0.10$). The changes in species as determined by the chi-square test indicated that three species (2, 3, and 18) showed important differences between higher- and lower-concentration SO_2 sites for changes in total number of observations between 1974 and 1978 and that 18 species showed no differences.

If the changes observed were caused by SO_2 emissions, SO_2 must be shown to cause increases and decreases in particular lichen species. However, the cause of an increase or decrease in a particular species cannot be proven conclusively. Observed changes in a particular species could result either from direct physiological effects of air pollutants on that species, or from indirect effects through competition with other species.

Air pollution monitoring has not documented high levels of SO_2 from the generating station. Maximum levels of 389 $\mu g/m^3$ for 1 h and 250 $\mu g/m^3$ for 3 h have been recorded. At any one location the frequency of SO_2 fumigations from the generating station of more than 50 $\mu g/m^3$ averaged only 1 to 2 times per month (Table 8) and each fumigation usually persisted for only 2 to 3 h (Table 5). Therefore significant or obvious injury from SO_2 would not be anticipated around this generating station. The average background level of SO_2 exceeded the average calculated increases in SO_2 from the generating station so that the small concentration difference between the calculated high and low SO_2 areas likely would not have much biological significance.

TABLE 24. NUMBER OF SITES FOUND TO HAVE EACH LICHEN SPECIES IN THE NE-FACING QUADRATS IN 1974 AND 1978 AND COMPARISON INDICES FOR THE CHANGES IN LICHEN DISTRIBUTION BETWEEN 1974 AND 1978

	Number of observations				Sorenson index†			
	Lower-SO_2 sites,		Higher-SO_2 sites,		Lower-SO_2 sites,	Higher-SO_2 sites,		Chi-square
Species* number	1974	1978	1974	1978	1974 to 1978	1974 to 1978	L-H‡	values§, 1974 to 1978
1 cr	94	92	81	69	0.76	0.87	-0.11	NS
2 cr	35	24	10	30	0.51	0.47	+0.04	$p<0.05$
3 cr	17	13	5	14	0.53	0.14	+0.39	$p<0.05$
8 f	63	86	37	58	0.74	0.73	+0.01	NS
12 cr	46	49	9	13	0.72	0.85	-0.13	NS
14 cr	16	9	11	9	0.41	0.49	-0.08	NS
16 cr	54	48	26	25	0.76	0.75	+0.01	NS
18 cr	14	13	11	2	0.38	0.09	+0.29	$p<0.05$
20 cr	87	97	40	50	0.78	0.74	+0.04	NS
21 f	45	51	23	16	0.63	0.71	-0.08	NS
22 f	21	25	8	19	0.80	0.59	+0.21	NS
23 f	38	53	48	40	0.81	0.69	+0.12	NS
26 f	59	61	31	42	0.78	0.72	+0.06	NS
30 f	22	17	25	24	0.68	0.65	+0.03	NS
32 cr	12	10	13	11	0.51	0.68	-0.17	NS
35 f	162	163	106	102	0.96	0.94	+0.02	NS
36 f	36	42	14	13	0.81	0.36	+0.45	NS
38 f	27	13	12	4	0.65	0.25	+0.40	NS
39 f	30	29	18	15	0.56	0.73	-0.17	NS
42 cr	17	18	6	16	0.59	0.36	+0.23	NS
46 cr	51	62	22	25	0.78	0.60	+0.18	NS

*cr is crustose, f is foliose.

†Sorenson-index values were calculated using relative number of quadrats per site at appropriate sites for each species, not total number of observations per species for lower- or higher-SO_2 sites.

‡L is Sorenson-index value for lower-SO_2 sites and H is Sorenson-index value for higher-SO_2 sites. If L-H is positive, greater change has occurred at higher-SO_2 sites; if L-H is negative, less change has occurred at higher-SO_2 sites.

§Chi-square values were calculated using total number of observations per species for lower- or higher-SO_2 sites.

Growth Anomalies on Particular Lichen Species

Comparison of these growth anomalies at higher- and lower-concentration SO_2 sites indicated little differences. Only the white spotting of lobe tips on *P. bolliana* increased on samples from the higher concentration SO_2 sites and this increased injury was primarily at only two sites, 13 and 31, which were 48 km NE and 9.7 km SW of the station (Table 25). Most of the injury was found on the samples from the NE side of the trees rather than on the side of the trees facing the station. These two sites were those with predominantly the Hill's oak species. The lichen communities at these sites did not appear unusual in the ordination (Figure 11, Figure 12), nor were community changes unusual at these two sites between 1974 and 1978 (Table 21). Unfortunately no records of these anomalies were taken during the 1974 sampling.

CONCLUSIONS AND RECOMMENDATIONS

Species composition and natural variation of communities of lichens growing on black-oak bark in the vicinity of the Columbia Generating Station have been described, and comparisons have been made between samples collected before (1974) and with operation (1978) of the generating station. The homogeneity of the sample sites for tree and lichen composition was determined by ordination procedures.

Comparison of lichen communities before and after the generating station went into operation have documented changes in the lichen communities involving increases and decreases in the number of species and frequency of occurrence of each species. These changes have been documented in areas predicted to receive the higher amounts of SO_2 from the generating station (2 to 4 $\mu g/m^3$ annual average) and lower amount of SO_2 from the generating station ($< 2\ \mu g/m^3$ annual average). Sites in the higher concentration SO_2 group were shown to have changed slightly more as a group between 1974 and 1978 than sites in the lower concentration SO_2 group (Table 21).

No lichen species were eliminated from higher concentration SO_2 sites by the operation of the generating station, and the documented statistical changes were for species not found at all sites and only in a few of the quadrats at each site (Table 23, Table 24). The species *Lepraria membranacea* (18) was the only species to decrease significantly in occurrence with operation of the generating station, and two species, *Bacidea chlorantha* (2), and *B. chlorococca* (3), increased in occurrence with operation of the generating station.

Although it is unlikely that the recorded changes in individual lichen species resulted from increased SO_2 emissions from the generating station, this possibility cannot be excluded entirely. Changes in individual lichen species might result either from SO_2 emissions directly affecting particular species or affecting the habitat of the oaks in a manner that would indirectly affect an individual lichen species. With both dirns from the generating station, this possibility can not be excluded entirely. Changes in individual lichen species might result either from SO_2 emissions directly

TABLE 25. DISTRIBUTION OF SPECIMENS OF *PARMELIA BOLLIANA* WITH WHITE ACCUMULATIONS ON LOBE TIPS

		NE quadrats		Other quadrats	
Site number	Distance (km) and direction from generating station	Number of specimens collected	Number of specimens with accumulations	Number of specimens collected	Number of specimens with accumulations
		HIGHER SO_2 SITES			
1	6.4 SE	2	0	3	0
2	9.7 SE	0		2	0
7	7.2 E	1	1	1	0
8	10.5 E	2	0	0	
9	14.5 E	3	1	2	0
13	4.8 NE	4	3	1	1
14	8.9 NE	1	0	2	0
20	9.7 NNW	1	0	1	0
30	4.8 SW	1	0	0	
31	9.7 SW	4	3	0	
	Total	19	8	12	1
		LOWER SO_2 SITES			
3	14.5 SE	1	1	1	0
15	15.3 NE	1	0	1	0
16	33.0 NE	7	0	1	0
17	51.5 NE	7	0	5	0
21	17.7 NNW	1	0	1	0
22	33.0 NNW	1	1	0	
23	46.7 NNW	2	0	3	0
25	4.0 W	3	1	5	0
26	9.7 W	1	0		
27	14.5 W	1	0		
32	16.1 SW	2	0		
	Total	27	3	17	0

affecting particular species or affecting the habitat of the oaks in a manner that would indirectly affect an individual lichen species. With both direct or indirect effects of SO_2, stimulation or depression of growth of individual species could occur.

A number of specimens *P. bolliana* (22) exhibited a growth anomaly white accumulations on the lobe tips in the 1978 sampling, which may have been caused by SO_2 from the generating station (Table 25). No observations of this injury were made only in the 1974 sampling to determine if the accumulations were present before the generating station began operations.

Some changes in lichen communities from 1974 to 1978 occurred at all sites and apparently are not related to the operation of the generating station; e.g., significantly more lichen species were identified in the sampling in 1978 than in 1974.

Further investigations are needed to provide conclusive data on SO_2 effects on lichen communities near the station. Monitoring of lichen communities should be conducted every 4 yr to document changes in the communities. In addition to community studies, more direct monitoring of selected lichen species is needed to allow assessment of the existence and relative importance of direct and indirect effects of SO_2 on lichens. Permanent lichen quadrats should be surveyed once a year to gather data on average growth rates of the common lichen species, variation in their annual growth rates, and appearance of growth anomalies. The species selected should include species that were present in a significant portion of the sampled quadrats, species that were documented to have significant changes between 1974 and 1978, and species that were documented to have growth anomalies, namely, *P. bolliana* (22), *P. caperata* (23), *P. rudecta* (26), and *Physcia millegrana* (35).

SECTION 6

SAMPLING ALFALFA FIELDS

INTRODUCTION

The purpose of the study--begun in 1971--was to document the type and amount of field damage to herbaceous crops before and after initiation of operations at the Columbia Generating Station near Portage, Wis. Alfalfa (*Medicago sativa* L.) was the major crop monitored because it is sensitive to sulfur dioxide (SO_2), and its symptoms are distinctive for SO_2 pollution. Another reason for monitoring alfalfa is because of its wide distribution near the station and its value to dairy farming. In the vicinity of the alfalfa sampling sites, two other pollutant-sensitive plants--giant ragweed (*Ambrosia trifida* L.) and blackberry (*Rubus* sp.)--were observed for symptoms of pollutant injury.

Monitoring of the plants provided an inexpensive means of determining if high concentrations of pollutants were present around the station. Alfalfa was particularly useful for monitoring because it has succulent new growth during most of the growing season. Growth is initiated early in the spring and usually is harvested at least twice during the growing season until plants are killed by frost late in the fall.

Alfalfa is injured by low levels of SO_2 in the field and in controlled environments. Under field conditions, exposures of 0.4 ppm (1,000 $\mu g/m^3$) for 17 h have produced visible injury symptoms (Katz 1949) and in controlled environments exposures of 0.5 ppm (1,300 $\mu g/m^3$) for 4 h have produced injury (U.S. Environmental Protection Agency 1973). In controlled-environment studies, discussed in section 8, a minimum threshold level of 0.7 ppm (1,800 $\mu g/m^3$) SO_2 for 4-h exposures was found for alfalfa.

Alfalfa also is relatively sensitive to photochemical oxidants, primarily ozone (O_3) (U.S. Department of Health, Education and Welfare 1970), which are occasionally found at high levels from background sources during the growing season in the station area. In controlled-environment exposures a minimum threshold level of 0.2 ppm (500 $\mu g/m^3$) for 4 h produced injury.

Alfalfa also is sensitive to exposures of low levels of SO_2 and O_3 in combination. Injury has been produced when both pollutants in combination were tested at lower concentrations than when pollutants were tested separately. In controlled-environment exposures a minimum level of 0.36 ppm (940 $\mu g/m^3$) SO_2 and 0.13 ppm (260 $\mu g/m^3$) O_3 for 4 h produced injury.

The symptoms of SO_2 injury on alfalfa are well documented and usually distinguishable from O_3 injury (Jacobson and Hill 1970, Katz 1949). The earliest symptom of SO_2 injury to alfalfa, as indicated from laboratory exposures, is a noticeable stiffening of the leaves as though the cells had greatly increased in turgidity. The turgidity increases until certain areas in the leaf suddenly become flaccid and appear water-soaked. These flaccid areas bleach after a few hours almost to an ivory color and result in large areas of intercostal necrosis (dead areas). The necrosis is limited usually to the marginal areas. Full-grown functional leaves show injury first and are more severely injured than partially-developed leaves.

Symptoms of O_3 injury on alfalfa are more variable, with upper-surface necrosis, bifacial necrosis, and chlorosis (yellowing) commonly observed. Injury is more often spread over the entire leaf in contrast to the more marginal injury with SO_2. Injury symptoms caused by combinations of the pollutants are not distinct but tend to be more similar to those of exposure to O_6 alone (Reinert 1975).

Symptoms of SO_2 injury on giant ragweed also are well documented and distinct. The injured areas become bleached and the edges of the leaves curl, giving a cup-shaped form to the leaf that is distinctive for SO_2 injury. The symptoms of SO_2 injury on blackberry consist of a red-brown necrosis that can usually be distinguished from other forms of injury.

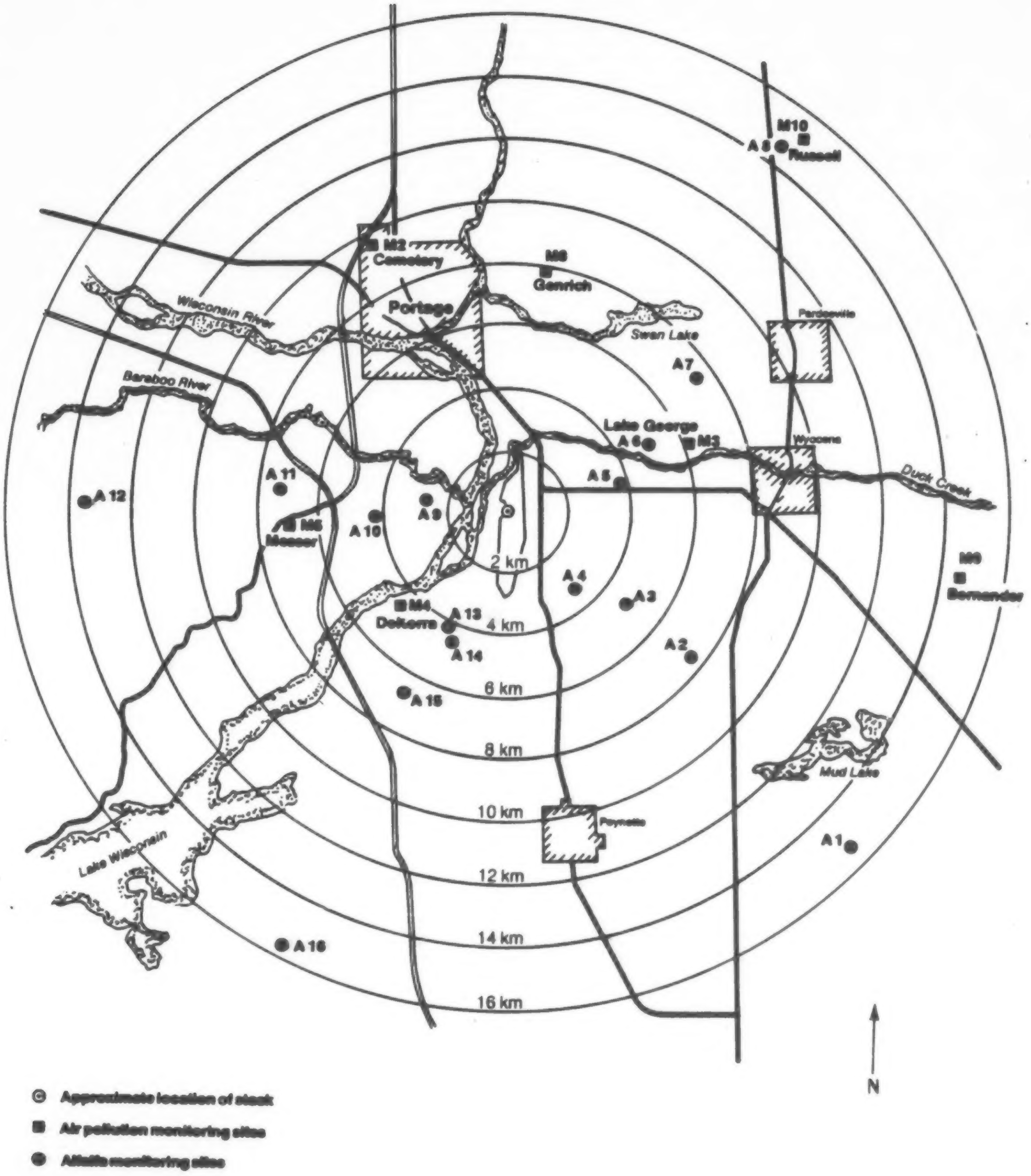
METHODS

Site Selection

A permanent network of monitoring sites was established in 1971, with sites located at approximately 3, 5, 8, and 16 km from the generating station in each of the four directions, namely, southwest, west, northeast, and southeast (Figure 15). Each site was located within an existing vigorously-growing alfalfa field. All fields were privately-owned, and permission was obtained to sample each site for as long as the monitoring program continues. Sampling was begun in the spring of 1972. In subsequent years if the field was planted in another crop or the alfalfa stand became very poor, a new field was chosen within 0.5 km of the one previously sampled. The bar graphs in Figure 16 indicate the number of years an individual sampling location was used and when locations were changed. Detailed maps of all sampling locations are given in Appendix E.

Sampling Methods

In each field a center point was selected approximately 18 m (60 ft) from the nearest road or field boundary. From this center point, subsampling plots were marked off at distances of 9 m (30 ft) N, S, E, and W of the sampling point. For each plot a 0.2 m^2 area was marked off. Alfalfa in this area were examined and scored for the degree of chlorosis and necrosis present on the leaves. The leaves showing injury were scored and the extent of the surface area damaged on the leaf was estimated. These figures were multiplied to obtain the total leaf area affected. Injury was recorded separately for each of three parts of the alfalfa plant, i.e., the



M10
A 8
Russell
M2
Cemetery
M8
Genrich
Portage
Wisconsin River
Swan Lake
Pardeeville
A7
Baraboo River
Lake George
A 6
M3
Wyocena
A 5
Duck Creek
A 11
A 12
A 9
M6
Mercer
A 10
2 km
M9
Bernander
A 4
A 3
M4
Dekorra
A 13
4 km
A 14
A 2
6 km
A 15
8 km
Mud Lake
10 km
Poynette
A 1
Lake Wisconsin
12 km
14 km
A 16
16 km
N
Approximate location of stack
Air pollution monitoring sites
Alfalfa monitoring sites

Figure 15. Location of alfalfa and air monitoring sites around the Columbia Generating Station.

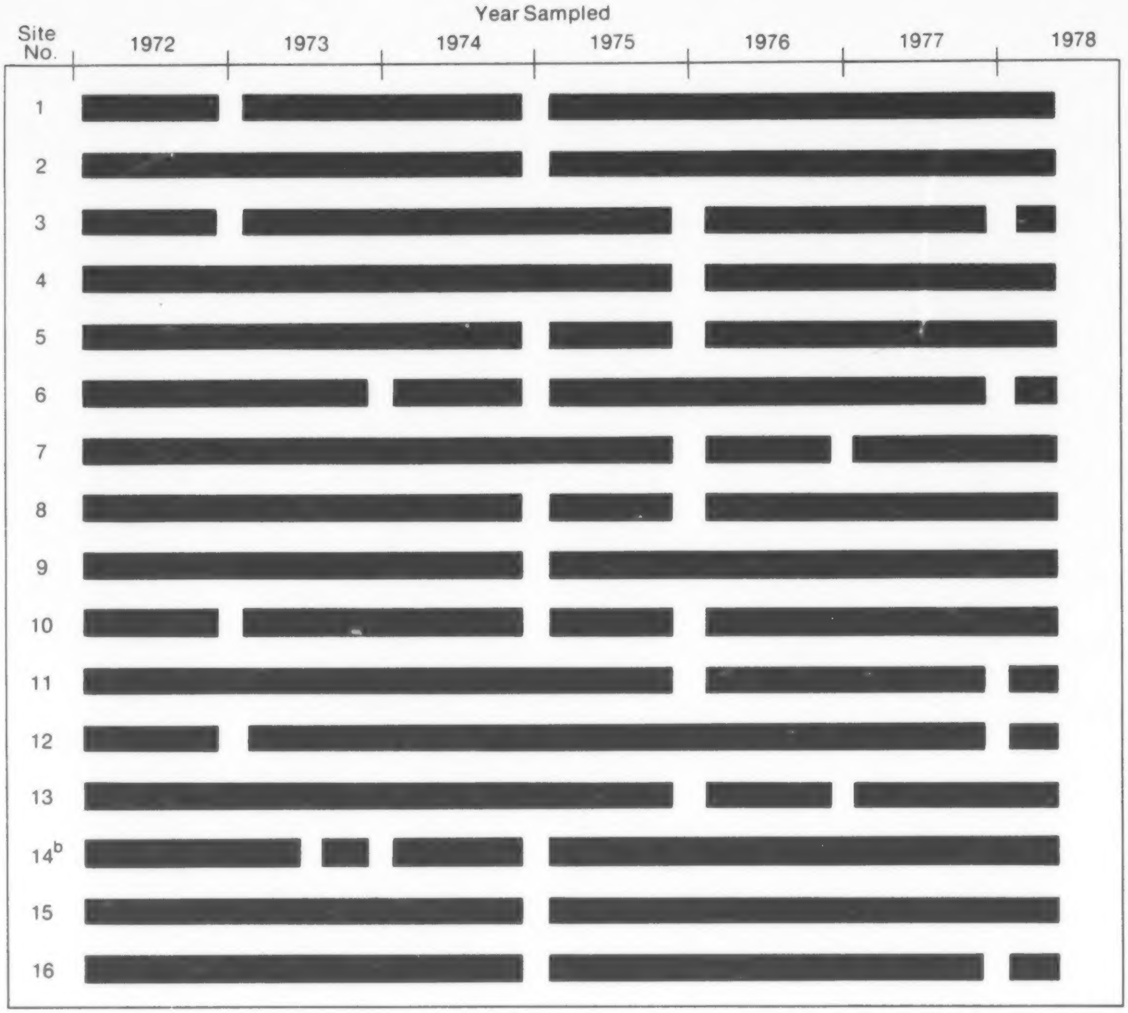


Figure 16. Sampling period for fields at each sampling site. A break in a bar indicates that a new field within .4 km was selected for sampling.

lower-, the middle-, and the upper-thirds. These separations were subjective, and considerable variation was obtained from field to field because of differences in plant maturity and vigor in the different stands.

Possible causes of leaf chlorosis and necrosis were evaluated in the field. Symptoms were compared with those documented by Rohweder et al. (1972) including common fungal, bacterial, and viral diseases; nutrient deficiencies; insect infestations; and environmental stresses such as water stress, freezing, and sunscald. If the cause of the injury symptoms was questionable, samples of injured alfalfa leaves were placed in plastic bags and subjected to laboratory examination. To document the injury symptoms, photographs of alfalfa-injury symptoms were made for whole plants in the field and individual leaves after return to the laboratory.

Measurement of alfalfa yield was made by harvesting all plants within a 0.2 m area of each of the four plots in each field. Fresh weights of the samples were taken immediately, and dry weights were taken after samples had been dried for 1 week at 40°C. The dry weights for alfalfa from each of the four plots were averaged to obtain a dry weight for each site. This dry weight was adjusted to indicate alfalfa yield at each site in grams per meter squared and tons per acre at 12% moisture.

Sites were sampled three times during each summer, i.e., a few days before the normal harvesting times for farms in the area. The first samples were taken in late May or early June, the second in late July or early August, and the third in late September. Sampling procedures for the first and second visits were as described above. At the third visit, field samples were not taken because of the wide variation in harvesting times, but photographs and records were taken of the types of plant injury in each field.

During 1973 and 1978, the dried alfalfa samples from the June harvests were held for analysis of sulfur (S) content. Samples were separated to provide only leaves of the alfalfa plants for analysis. This separation was necessary because leaves have a much higher S concentration than stems, and comparisons would not have been precise between samples that had different proportions of stems and leaves (Chapman 1966, Rominger et al. 1975). Leaves were ground and analyzed by X-ray fluorescence (Jenkins and Devries 1973).

Soil samples were obtained from each sampling site during 1978 to determine soil type. At each site, a soil sample was taken from the field that was sampled for alfalfa during 1978. The fields usually were considered to be representative of the soil types for neighboring fields that were sampled in preceding years unless they were more than 100 m apart or on different topography in which case the soil was sampled. Samples were taken from the top 15 cm of the soil and were analyzed at the State Soil Testing Laboratory at Marshfield, Wis. The soil types ranged from sand to loam for the different fields (Table 26).

TABLE 26. SOIL TYPES AT ALFALFA SAMPLING SITES NEAR THE COLUMBIA GENERATING STATION

<table>
<tr><th>Site</th><th>1972</th><th>1973</th><th>1974</th><th>1975</th><th>1976</th><th>1977</th><th>1978</th></tr>
<tr><td>1</td><td colspan="3">Loam*</td><td colspan="4">Sandy Loam</td></tr>
<tr><td>2</td><td colspan="3">Sandy Loam*</td><td colspan="4">Loam</td></tr>
<tr><td>3</td><td colspan="6">Sand*</td><td>Sandy Loam</td></tr>
<tr><td>4</td><td colspan="7">Sandy Loam</td></tr>
<tr><td>5</td><td colspan="4">Loamy Sand*</td><td colspan="3">Sandy Loam</td></tr>
<tr><td>6</td><td colspan="6">Sand*</td><td>Loamy Sand</td></tr>
<tr><td>7</td><td colspan="4">Sandy Loam*</td><td colspan="3">Loamy Sand</td></tr>
<tr><td>8</td><td colspan="7">Loam</td></tr>
<tr><td>9</td><td colspan="7">Loamy Sand</td></tr>
<tr><td>10</td><td colspan="7">Silt Loam</td></tr>
<tr><td>11</td><td colspan="7">Silt Loam</td></tr>
<tr><td>12</td><td colspan="7">Silt Loam</td></tr>
<tr><td>13</td><td colspan="7">Sandy Loam</td></tr>
<tr><td>14</td><td colspan="4">Sand*</td><td colspan="3">Loamy Sand</td></tr>
<tr><td>15</td><td colspan="3">Sandy Loam*</td><td colspan="4">Loamy Sand</td></tr>
<tr><td>16</td><td colspan="7">Loamy Sand</td></tr>
</table>

*Field plowed and planted to corn or grain. A nearby field selected for sampling.

At many of the sites previously identified, stands of native giant ragweed and blackberry were observed for injury symptoms from SO_2 (Table 27).

TABLE 27. PRESENCE OF POLLUTANT SENSITIVE SPECIES AT SAMPLING SITES

Site	Alfalfa	Blackberry	Giant ragweed
1	x		x
2	x		
3	x		x
4	x		
5	x	x	
6	x		
7	x	x	
8	x		x
9	x	x	x
10	x	x	x
11	x	x	x
12	x		x
13	x		x
14	x	x	
15	x	x	
16	x		x

Statistical Analysis

Analysis of variance procedures were used to determine differences among sites and years for leaf injury, yield, and S content of the alfalfa. For each year, only data from the first (June) harvest was used for analysis because they were most complete for all sites. At the July and September harvest times, fields were at varying levels of maturity because the farmers made the June harvests at different times. Thus, the July data were not used because injury ratings, yield and S content data from several sites each year were not obtained. For the September harvest no yield and S content data were obtained, and injury data for this harvest only were ranked.

To simplify the analysis, average injuries and yield values for each site were used rather than the separate values for the four plots. Little variability in individual-plot values was found unless the alfalfa stand was thin. Data for individual plots are available in the data bank of the project. For the analysis of S content, however, the S-content values for each of the four separate plots were used.

In addition to the comparisons between individual years and sites, additional comparisons were made between pre-operational years (1972 to 1974) and the post-operational years (1976 to 1978) and among sites predicted to receive different amounts of SO_2 from the station. Data for 1975 were not used because the generating station initiated operation in the middle of the growing season. A factorial design was used to compare plant responses at different sites before and after initiation of station operations, with individual years nested within the pre- and post-operational periods. A factorial design also was used to compare sites predicted to have different amounts of SO_2 emissions from the station. Alfalfa sites 2, 3, 4, 5, 6, 7, 13, and 14 were included in one group because they were located in areas predicted to receive an annual average of 2 or 3 μg (0.008 to 0.012 ppm) SO_2 from the generating station (Figure 17). Predictions were calculated for 1975 SO_2 emission data using a mathematical model developed by Ragland and Goodell (in press). The alfalfa at sites 1, 8, 9, 10, 11, 12, 15, and 16 were included in a second group because they were located in areas predicted to receive an annual average < 2 μg ($<$ 0.008 ppm) SO_2 from the generating station. This breakdown of SO_2 sites was used because increases in SO_2 with station operation are not large and therefore a significant difference between pre- and post-operational alfalfa responses only would be demonstrated with an average of several sites. For this analysis, individual years were nested within pre- and post-operational years.

RESULTS AND DISCUSSION

No symptoms of SO_2 injury on alfalfa, blackberry, or giant ragweed were observed at the sampling locations during the period of the study. Examination of the data on concentrations of SO_2 found in the air with continuous monitoring (section 3) did not indicate any levels high enough to produce damage to these plants. The maximum recorded levels of 389 $\mu g/m^3$ for 1 h and 250 $\mu g/m^3$ for 3 h are considerably below the levels of 1,500 $\mu g/m^3$ for 1 h and 1,100 $\mu g/m^3$ for 3 h that are required for visible threshold injury to alfalfa and other sensitive plants. The effects of SO_2 on alfalfa would have been most likely to occur when elevated concentrations of O_3 also were present, but high concentrations of SO_2 and O_3 simultaneously were recorded only rarely.

At times, individual plants in different fields exhibited a bleached injury symptom that could be mistaken for SO_2 injury; however, the bleached areas were distinct small spots dispersed over the leaf, which is not characteristic of SO_2 injury. Scientific examination indicated that this injury resulted from root injury that produces K-deficiency symptoms in the above-ground tissues.

The amount of chlorosis and necrosis on the plants was not increased by station operations. Data for the first harvest are shown in Table 28, and complete data for all harvests are included in Appendix F. Comparison of the injuries for 1973 to 1975 and 1976 to 1978 for the top-, middle-, and bottom-portions of the plants showed no significant differences except for an increased amount of chlorosis in the middle part of the plants during operational years. No evidence of increased chlorosis or necrosis at the sites predicted to receive larger amounts of SO_2 from the station was observed during 1976 to 1978.

Significant differences in chlorosis and necrosis on plants were recorded in different years (Table 28). These differences were correlated

Air Pollution in Micrograms per Cubic Meter
1976 Annual Average

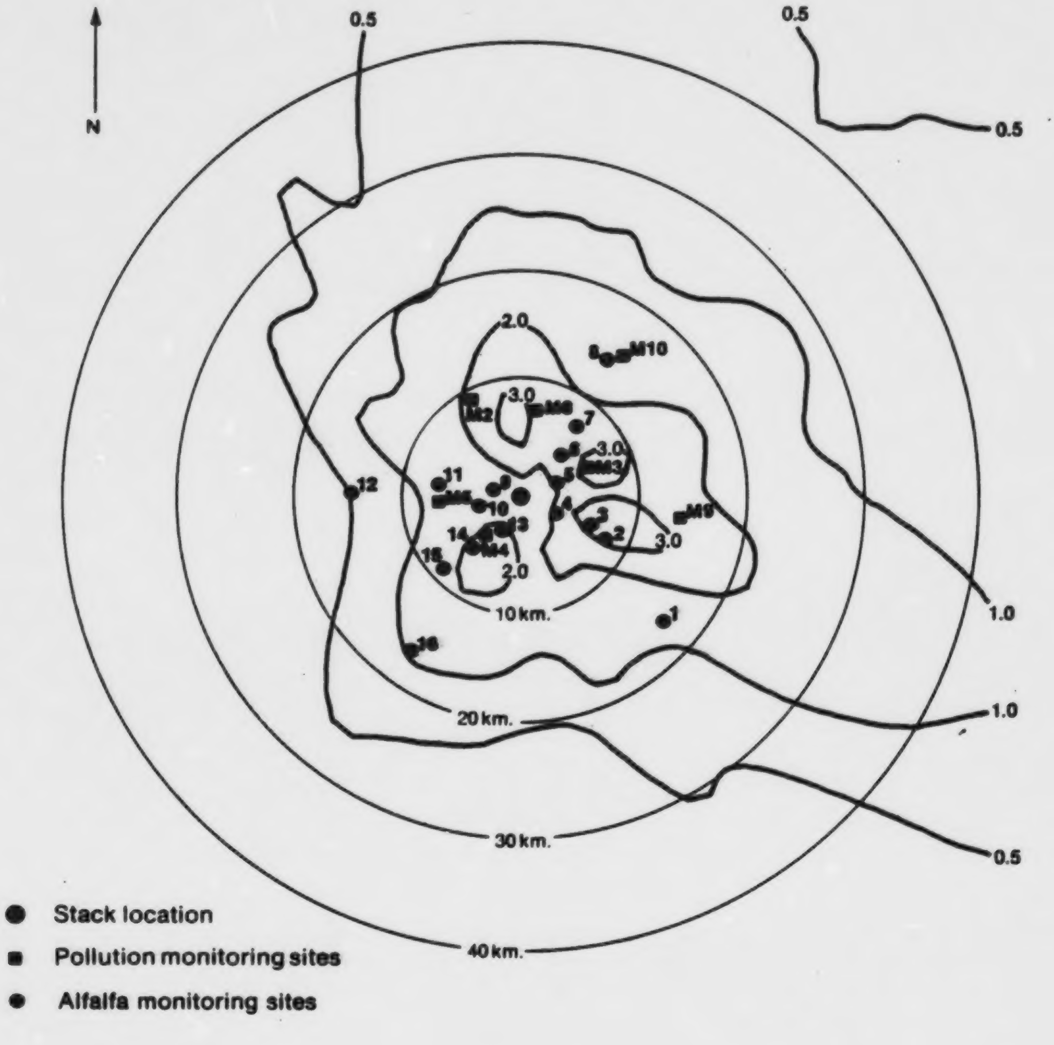

N
0.5
0.5
0.5
2.0
8
M10
3.0
M2
M6
7
6
3.0
M3
11
12
9
M5
10
5
4
3
2
M9
3.0
14
13
15
M4
2.0
10 km.
1
1.0
16
1.0
20 km.
30 km.
0.5
40 km.
Stack location
Pollution monitoring sites
Alfalfa monitoring sites

Figure 17. Alfalfa monitoring sites around the Columbia Generating Station and isopleths of predicted ground level SO_2 ($\mu g/m^3$) as a result of generating station operations.

with the severity of winter injury in the area and weather conditions during the growing period of the crop and did not appear to bear any specific relationship to SO_2 emissions from the station.

Table 28. AVERAGE PERCENTAGE OF CHLOROSIS AND NECROSIS OF ALFALFA LEAVES AT JUNE HARVEST FOR ALL MONITORING SITES (1972 TO 1978)

	Chlorosis of leaves			Necrosis of leaves		
Year	Lower third	Middle third	Upper third	Lower third	Middle third	Upper third
1972	30	16	7	15	8	3
1973	40	15	2	12	4	1
1974	45	15	2	11	4	1
1975	53	20	5	19	5	1
1976	52	28	3	18	6	2
1977	41	20	5	23	10	2
1978	41	22	1	20	11	6
p (all years)	0.05	0.05	NS	NS	0.05	0.05
p (before and after)	NS	0.05	NS	NS	NS	NS

Measurements of alfalfa yields indicated wide variations in different years and among monitoring sites but no evidence exists of injurious effects from the station. June harvest yields are shown in Table 29. Analysis of variance indicated no significant difference in yields of alfalfa for 1976 to 1978 compared to 1972 to 1974. The large differences between individual years before and after the station began operations apparently resulted from different temperature and moisture conditions over the different growing seasons. The coefficient of variation for alfalfa yields among the different years averaged 32%. This large coefficient of variation shows that yield reductions caused by SO_2 would have to be quite large and data would have to be accumulated over several years before slight injury or stimulatory effects from SO_2 could be documented statistically. The variation in yield between fields also was considerable, averaging 25% for all years.

After the sites were partitioned into areas predicted to receive different levels of SO_2 from the station, analysis of variance of dry weight of alfalfa from the June harvest indicated no significant difference between these areas (Table 30). The sites predicted to receive the larger amount of SO_2 did have lower yields, but this was true before as well as after the station began operations. Thus, the comparison provides no evidence of impact from station operation.

The S content of alfalfa leaves was significantly greater--by approximately 20%--in 1973 compared to 1978 (Table 31). Although large differences in S content at different sites were observed, with some sites as low as 0.26% and others as high as 0.48%, the differences were not significant when the two sampling times were averaged. The coefficient of variation between individual samples was only 17% for 1973 and 9% for 1978, indicating good precision for the determination. Sites predicted to have the greater amounts of SO_2 from the generating station had less S in leaves than the other sites in 1973 and 1978 (Table 32). The decreases were not significant at the 5% level.

The increased levels of S found in the tissues in the 1978 harvest from most of the sampled fields likely resulted from particular environmental conditions during 1978 that increased S uptake by plants in that year compared to 1973. The differences in S contents between the two sampling periods is less than the range of S concentrations recorded for field samples in successive years in other growing areas (Seim et al. 1969). Thus, no particular significance can be assigned to this increase in tissue S. The concentrations of S found in the alfalfa samples in 1978 were almost twice the concentrations recorded commonly for alfalfa (Seim et al. 1969, Hoeft and Walsh 1975, Rominger et al. 1975). High values were obtained in these analyses because stems were not included. Analysis of the separate parts of plants has shown that the concentration of S in leaves is about twice the concentration in stems (Chapman 1966, Rominger et al. 1975). Therefore, the concentrations of S found in the 1973 and 1978 samples were not excessive, and no deleterious effects to the plants would be expected at these concentrations (Hoeft and Walsh 1975). In fact, some data demonstrate that S levels in alfalfa below 0.3% can be limiting to the growth of the plant (Hoeft et al. 1973). Therefore, the alfalfa at several of the sites probably benefited from the added S from the station. Fertilization studies conducted in 48 alfalfa fields throughout Wisconsin have demonstrated that slightly more than 30% of the fields studied had a significant yield increase with added S (Hoeft et al. 1973).

An additional factor that may have affected differences in alfalfa yields and S-content data in areas predicted to receive higher concentrations of SO_2 and those predicted to receive lower concentrations from the station was the difference in predominant soil types in the two areas. The higher SO_2 areas--located east of the generating station--were on sandy soils, whereas the lower SO_2 areas--located west of the station--were mostly silt or loam soils. Alfalfa growing on loam and silt-loam soils is subject to a lesser degree of moisture and temperature stress than alfalfa growing on sandy soils.

TABLE 29. ALFALFA YIELD (g/m^2) FOR JUNE HARVEST FROM INDIVIDUAL SAMPLING SITES*

	Before operation of the Columbia Generating Station			With operation of the Columbia Generating Station			
Site	1972	1973	1974	1975	1976	1977	1978
1	393	343	439	548	563	491	470
2	488	505	673	359	716	369	610
3	262	355	425	313	250	179	—
4	318	276	323	373	—	304	337
5	402	314	436	284	443	277	353
6	280	345	258	137	332	127	255
7	402	327	301	255	221	270	633
8	486	389	344	356	292	419	423
9	486	437	430	299	539	268	427
10	514	404	404	424	365	432	367
11	346	429	764	783	419	614	494
12	514	355	404	374	785	482	333
13	280	383	753	435	424	396	526
14	299	402	436	328	526	287	505
15	402	339	285	477	527	241	416
16	346	343	350	260	283	307	495
Average	388	372	439	375	445	341	442

*Multiply numbers by 0.005 to obtain tons per acre of harvested hay at 12% moisture.

TABLE 30. AVERAGE JUNE YIELDS OF ALFALFA AT SITES PREDICTED TO RECEIVE 2 TO 4 $\mu g/m^3$ SO_2 AND AT SITES PREDICTED TO RECEIVE < 2 $\mu g/m^3$ WITH OPERATION OF THE COLUMBIA GENERATING STATION

Years	Sites predicted to receive 2 to 4 $\mu g/m^3$ SO_2	Sites predicted to receive < 2 $\mu g/m^3$ SO_2
1972 to 1974 (before operation)	385.1*	414.4
1976 to 1978 (after operation)	380.9	435.5

*Correlations between each pair of numbers are not significant.

TABLE 31. PERCENTAGE OF S IN ALFALFA LEAVES FROM JUNE HARVESTS IN 1973 AND 1978*

Site	S (%)	
	1973	1978
1	0.45	0.40
2	--	0.46
3	0.30	--
4	--	0.34
5	0.31	0.38
6	0.26	0.36
7	0.33	0.43
8	0.33	0.44
9	0.32	0.41
10	0.48	0.45
11	0.36	0.45
12	0.37	0.44
13	0.31	0.44
14	0.38	0.40
15	0.36	0.40
16	0.32	0.41
Average†	0.35 ± 0.06	0.41 ± 0.04

*Average of four samples taken at each site.
†Average for 1978 samples is significantly greater ($p < 0.05$) than average for 1973 sample.

TABLE 32. AVERAGE S CONTENT (%) OF ALFALFA LEAVES FROM HIGH AND LOW SO_2 SITES FROM JUNE HARVESTS IN 1973 AND 1978

Years	High SO_2 sites	Low SO_2 sites
1973	0.32*	0.37
1978	0.40	0.42

*Average values for high and low SO_2 sites were not significantly different in 1973 or 1978.

SECTION 7

ALFALFA STUDIES IN OPEN-TOP FIELD CHAMBERS

INTRODUCTION

To supplement data obtained by sampling commercial alfalfa fields, the impact of air pollutants on alfalfa near the Columbia Generating Station was evaluated during 1976 with open-top field chambers. Open-top field chambers have been used to obtain a quantitative estimate of yield reductions for crops from air pollutants under field conditions (Heagle et al. 1973). The large cylindrical plastic chambers, about 3 m across and open at the top, are placed over plants in the field and are equipped with large blowers to move air through the chambers. Air entering the chambers passes through filters which remove ambient air pollutants so that plants can be grown under field conditions without airborne contamination. Control chambers without air filters are used to provide an estimate of the yield of the crop under ambient pollution levels. The use of control chambers permits correction for small effects of the chambers on plant growth. Open-top field chambers have been adopted widely to evaluate plant damage due to ambient air pollutants under the assumption that the environment of the chambers is not significantly different from the ambient environment (Heagle et al. 1973, Mandl et al. 1973, MacLean and Schneider 1976, Heggestad et al. 1977, Wukash and Hofstra 1977, Musselman et al. 1978). Detailed data on the magnitude of environmental differences between the chambers and open areas as determined in this study are discussed at the end of this section.

MATERIALS AND METHODS

Chamber Specifications and Set-up

Six chambers 2.4 m high by 3 m in diameter, similar in design to those detailed by Heagle et al. (1973), were borrowed from R. Howell of the Plant Stress Laboratory of the U.S. Department of Agriculture at Beltsville, Maryland. Arrangements were made to place these chambers in a 2-yr old alfalfa field at the junction of Military Road and County EE, 8.3 km N of the Columbia Generating Station and 1.5 km NE of Portage, Wis. This field was within 100 m of a continuous air-pollution monitoring station (Figure 1).

The field at this particular location was selected because it was considered to be representative of alfalfa fields in the area which could potentially be injured by emissions from the generating station. The field contained vigorously growing alfalfa planted 2 yr earlier and was uniform in topography, except for a slight N-S slope. (Variability in alfalfa growth because of this slight slope was considered to be one of the factors in the Latin-square design established for this analysis.) The field had sandy loam soil containing 68% sand, 24% silt and 8% clay and a soil sulfur (S) level of 5.6 kg/ha. This S level was low, and at this level a large percentage of alfalfa fields in Wis. would have increased yields with addition of S. The field also was selected because it was adjacent to an electric power line from which an extension could be run to supply electricity for the chamber blowers.

Cylindrical chambers were used to insure uniform air flow and pollutant distribution (Heagle et al. 1973, Mandl et al. 1973). Square or rectangular chambers are not desirable because they contain corners which slow air movement causing variability in plant size and pollution response. The structural components of the chamber system were designed to minimize environmental alterations that might affect the pollutant sensitivity of the plants (Heagle et al. 1973). The chambers were structurally-secure and able to withstand high winds and other adverse weather conditions. Furthermore, they were readily assembled, moved, and maintained. The structural skeleton of the chambers was made of light-weight aluminum with thin braces which minimized radiation reductions in the chambers.

The chambers could not prevent all flow of non-filtered air from the atmosphere into the chamber through the open top. Because of the cylindrical form with a sharp edge at the top, wind could tumble into the chamber. This turbulent mixing is greatest at high wind speeds which move a large amount of air into the chambers (Heagle et al. 1973). In this study no attempt was made to reduce this mixing effect, and the tops of the chambers remained open. A significant reduction of turbulent mixing was achieved in another study by installation of a baffle attached at a 45° angle around the top of the chamber (Kats et al. 1976). The baffle changes the geometry of the trailing edge so that wind is deflected from the top of the chamber and the rate of vertical air flow out through the top is increased.

The chambers in this study were covered with vinylchloride plastic film (Krene-KDA-2244 Union Carbide) which was stretched over the frame during April. As air temperature increased, the plastic expanded, slipped from the tops of the chambers, and had to be reattached.

The air-handling system of the chambers was designed to filter pollutants from the ambient air and to maintain a constant air flow through the chambers at a rate sufficient to minimize the entrance of polluted air into the top. The air-handling system consisted of a fiberglass particulate filter, squirrel-cage blower, and duct leading to the perforated lower panel (Figure 18). The blowers were fitted with 40.6-cm fans (squirrel-type) delivering 53.8 m^3/min at 0.6-cm static pressure. Air was forced through a plastic duct 50 cm in diameter into the lower double panel that enclosed the chamber. Air entered the growing area of the chamber through a large number of 2-cm holes spaced to a height of 1.2 m on the inner surface of the lower plastic panel. Three of the six chambers were

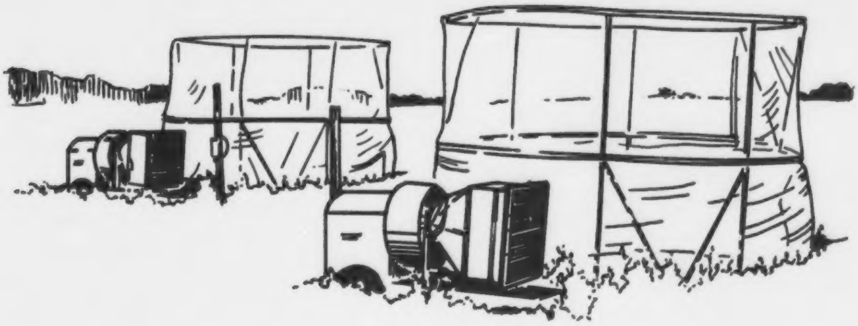


Figure 18. Open-top field chambers used to measure effect of ambient air pollutants on alfalfa yield. Air handling systems with motor, fan, and charcoal filter unit are seen on left of the plastic-covered chambers.

fitted with stainless-steel canister filters, each containing 20.5 kg of coconut shell activated charcoal (Barnebey Cheney grade CH). All six chambers were fitted with fiberglass particulate filters 5-cm thick for dust removal. To insure equal flow between chambers, air-flow readings were taken with an anemometer (Anemotherm Model 60) in the duct between the fan and the chambers. This procedure was necessary because in the chambers the large charcoal filters reduced the flow through these units compared to the air flow in the non-filtered chambers.

Air flow was balanced between chambers by removing the air duct leading from the blowers to the chambers and measuring the velocity of air at 12 positions within the duct with a hot-wire anemometer. The sensing element was positioned perpendicular to the air flow successively at eight equally spaced positions around the outer area of the duct 5 cm from the outside edge, and at four equally spaced positions near the center of the duct 18 cm from the outside edge. Average air flow was determined from the 12 readings. Differences in air flow between chambers were corrected by altering the size of the pulleys on the fans. Significant corrections were necessary to equalize flow between units containing charcoal filters and those without charcoal filters. After adjustments were made, the ducts were attached to each chamber.

The speed of air flow through the ducts at 840 liter/sec with squirrel-cage blowers was lower than the 1,180 liter/sec obtained in chambers when axial-blade fans were used (Heagle et al. 1973). In addition, the squirrel-cage blowers resulted in non-uniform air flow through the duct with a band of lower air flow across the bottom of the ducts and a band of higher air flow across the top of the ducts. These air-flow differences could have resulted in uneven air flow into the chambers. The use of axial blade fans would have resulted in greater uniformity in air flow throughout the duct.

Balancing air-flow rates in the different chambers with the blower units separated from the chamber duct did not provide a uniform air-flow rate when the blower units and chambers were reattached. Measurements within the chambers indicated different flow rates in filtered and non-filtered chambers. Problems were caused apparently in the attempt to balance air flows when the ducts were removed from the chamber. With reattachment, air formed a back pressure against the blower because of the restriction of air flowing out of the holes in the lower chamber wall. The different fan speeds in the filtered and non-filtered chambers could have caused different pressures to develop in these two types of chambers, causing different air-flow rates after reattachment. Better equalization of air flow would have been possible if the ducts had remained attached to the chamber and measurements had been taken by placing the anemometer sensor into the ducts through small holes. Accurate air flow measurements could have been obtained also by a carefully regulated flow of gas--such as CO--into the blowers and by measurement of the gas concentration in the chambers (R. Thompson, personal communication).

Nine plots of alfalfa, three of which had chambers with charcoal filters, three with chambers without charcoal filters, and three plots without chambers, were established using a Latin-square design with plots 6.1 m apart. Each plot was divided into quarters or quadrants comprising four equal subplot areas in northern, southern, eastern, and western directions delineated with 5.0-cm high, 2-mm wide aluminum strips. An area 0.3 m in width was separated with aluminum strips at the outer edge of each subplot area adjacent to the plastic wall. The chambers were placed in the field and the fans started on 13 April 1976. At this time the alfalfa in all plots was approximately 5.0 to 7.5 cm high. All plots were treated with Kerb herbicide on 17 April to kill grass (principally timothy and quackgrass) in the plots.

Air-pollutant levels were obtained at permanent monitoring sites for the period of this experiment (section 3). From 1 April to 15 June 1976, ozone (O_3) levels were obtained from data collected at the Messer site located 11.2 km W of the field plots, and levels of nitric oxide (NO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) were obtained from data from the Lake George site, located 8 km S of the field plot. From 15 June to 31 August 1976, levels of pollutants were obtained from data collected at the Genrich site located 50 m from the field plots. The hourly average values were examined to determine the occurrence of pollutant levels that might injure alfalfa.

The charcoal filters' effectiveness in removing oxidants from the ambient air was checked by monitoring oxidants in the center of the ducts leading from the blowers to the chambers with a Mast 724-1 oxidant meter. Oxidants were monitored for 20 min in each chamber and for 20 min in the ambient air between chamber measurements on only one day.

Plant-Injury Response

The alfalfa in each plot was harvested three times during the growing season to determine leaf injury, plant height, and yield. Harvests on 4 June and 22 July 1976 were made when plants were at approximately 10% of full bloom, and a final harvest was made on 2 September when plants were at approximately 50% of full bloom.

Plants were observed for necrosis, symptomatic of air-pollutant injury. The plants were scored for chlorosis resulting from environmental stress, disease, and insect injury. To estimate leaf chlorosis the percentage of leaves per quadrat and the percentage of the area of the leaves that were chlorotic was determined by visual examination. These values were multiplied together to find the percentage of the chlorotic leaf area per quadrat.

Plant height was measured by placing a meter rule in the center of each plot to determine average height of the alfalfa.

Alfalfa yield was measured by cutting off the plants 5 cm above the soil surface with an electric clipper and weighing the alfalfa immediately. Separate weights were obtained for the alfalfa from the center position of each of the northern, southern, eastern, and western quadrat areas. The alfalfa in the border (0.3-m wide areas along the wall) was harvested and discarded. For each quadrat area a weighed subsample of about 450 g was saved to determine alfalfa dry-weight for each subplot. Subsamples were dried for 7 days at 60°C in large forced-air dryers and for 1 day at 90°C in a constant-temperature oven.

Data for yield were compared with a 3 x 3 Latin-square analysis with quadrats as split plots (Steel and Torrie 1960). The Latin-square design was used so that variations in yield for the rows and columns in which the plots were located could be separated from the error variance. The data from the four quadrats in N, S, E, and W directions were included in the analysis as split plots.

RESULTS

No necrotic injury symptoms or yield differences attributable to air pollutants were seen with the alfalfa. Scoring for chlorosis indicated that plants were injured as a result of a combination of disease, insect injury, and environmental stress which differed slightly between treatments and at different harvests (Table 33). At the June harvests, chlorosis was about the same for all three treatments (6 to 7%). At the July harvest, chlorosis was lower for the open-area plants (11.4%) compared to the non-filtered (13.0%) and filtered-chamber plants (16.6%). At the September harvest, the alfalfa in the filtered chambers exhibited less chlorosis than the non-filtered and open-area chambers, but because of a very large difference between individual chambers, the difference between treatments was not significant. Alfalfa growing in the chambers was taller than that growing in the open areas at the first and third harvests. Average height of alfalfa for filtered and non-filtered chambers was 71, 40, and 38 cm for the June, July and September harvests, respectively, with averages of 53, 42, and 26 cm for the open-field plots at the three harvests.

Yields for the June, July, and September harvests (Table 34) showed no evidence of yield reduction in the non-filtered chambers and thus no effect from SO_2. In fact, the average yield for the non-filtered chambers in the June harvest was significantly greater (13%) than for the filtered chambers, and at the July and September harvests, yields between the non-filtered and filtered plots did not differ significantly. Although in the June harvests the yield from the chambers tended to be greater than from the ambient air plots, this result was reversed in the July and September harvests; thus the total yield over the season was not significantly different between chamber and ambient air plots.

Oxidant levels within the intake ducts of the three charcoal-filtered chambers were found to be only 10 to 20% of the ambient oxidant concentration. The oxidant level in the filtered chambers averaged from 12 to 20 $\mu g/m^3$ as compared to 78 to 106 $\mu g/m^3$ for the unfiltered chambers and open areas. At the time when these measurements were made data from the meteorological site located 10 km S indicated that the ambient wind speed was approximately 8.0 m/min from the S.

TABLE 33. AVERAGE PERCENTAGE OF CHLOROSIS FOR ALFALFA IN OPEN-TOP FIELD CHAMBERS AND OPEN AREAS NEAR THE COLUMBIA GENERATING STATION (1976)

Treatments	Harvest		
	June	July	September
Filtered chambers	7.1 ± 2.5y*	16.6 ± 3.8z	4.5 ± 5.4y
Non-filtered chambers	5.9 ± 0.9y	13.0 ± 5.0yz	19.8 ± 26.2y
Open areas	6.7 ± 3.3y	11.4 ± 3.7y	18.3 ± 8.6y

*Treatment means in a column followed by the same letter are significantly different at the 95% level.

TABLE 34. YIELD OF ALFALFA IN OPEN-TOP FIELD CHAMBERS AND OPEN AREAS NEAR THE COLUMBIA GENERATING STATION (1976)*

Treatments	Harvest (g/m^2)			
	June	July	September	Total
Filtered chambers	236 ± 80y†	99 ± 23y	84 ± 18y	419 ± 107y
Non-filtered chambers	270 ± 72y	111 ± 26z	92 ± 13y	473 ± 91y
Open areas	229 ± 64y	143 ± 18z	104 ± 21y	476 ± 93y

*Corrected to average yield at 12% moisture. Multiply by 0.005 to obtain yield in tons/acre.

†Treatment means in a column followed by the same letter are not significantly different at the 95% level.

The frequency distribution for air pollutants monitored during the experiment in the surrounding area indicates that SO_2 levels were < 20 μg/m^3 for 89% of the time. Only 14 1-h averages were above 120 μg/m^3, and the highest level recorded was 353 μg/m^3. The NO and NO_2 levels averaged 2 and 12 μg/m^3, respectively, and no levels above 80 μg/m^3 were recorded. Also, O_3 was present at all times during the study with 82% of the values above 80 μg/m^3 with 206 1-h averages above 200 μg/m^3. The maximum O_3 level measured was 263 μg/m^3.

DISCUSSION

A comparison of alfalfa in filtered and non-filtered chambers indicates that charcoal-filtering the air before it entered the chambers was not a factor affecting plant growth and yield. No injury symptoms were observed on alfalfa that could be attributed directly to O_3 or SO_2 during the entire growing season. This finding was anticipated because the maximum levels of these pollutants were below the threshold levels of 400 μg/m^3 O_3 and 1,800 μg/m^3 SO_2 required for injury to alfalfa. Low levels of SO_2 would have been more likely to stimulate alfalfa than inhibit it because of the low level of S in the soil and the recognized S-deficiency in alfalfa fields in Wis. (Hoeft et al. 1973). The combined ambient levels of O_3 and SO_2 were potentially of greatest concern since combinations of SO_2 as low as 262 μg/m^3 and O_3 at 196 μg/m^3 for 4 h have been found to injure alfalfa in controlled environments (U.S. Environmental Protection Agency 1973). The highest combined level recorded near the generating station for a 1-h period was 353 μg/m^3 for SO_2 and 263 μg/m^3 for O_3 (section 3). Although the recorded levels for O_3 is only slightly below the minimum threshold concentration for injury, the sensitivity of alfalfa plants to pollutants was decreased during the 1976 growing season because the lack of rainfall placed them under significant water stress.

The chlorosis injury observed apparently was caused by factors other than air-pollution injury because significantly more chlorosis manifested itself in the filtered chambers than in the non-filtered chambers at the first and second harvests.

The shorter height of alfalfa growing in open areas compared to alfalfa in chambers probably was caused by greater atmospheric moisture stress which reduced leaf and stem expansion in the plants grown in the open areas. The increased atmospheric moisture stress was documented through use of atmometers and is reported in the last part of this section.

There were no important differences found in yield of alfalfa in chamber plots compared to open-area plots, but the large variability between plots greatly reduced the precision of comparisons. Alfalfa appeared to grow more rapidly in the chambers than in open areas early in the season but this was not evident later in the season. Differences between chambers and open areas also were evident late in April when a frost caused alfalfa injury in open areas but not in the chambers.

EVALUATION OF ENVIRONMENTAL PARAMETERS IN OPEN-TOP FIELD CHAMBERS

Open-top field chambers have been used to assess the impact of air pollutants on plant growth because this is the only way that ubiquitous pollutants can be studied under field conditions. Plant response has been assumed to be similar to the response of plants to ambient environments (Taylor 1975). This assumption has been supported by investigations of differences in the microenvironment between chambers and open areas with evaluations of radiation intensity, air temperature, and air flow (Heagle et al. 1973, Heggestad et al. 1977, Heagle et al. 1979). These studies have demonstrated some small differences. Radiation was slightly reduced and air temperature was slightly higher in chambers than in open areas. Air flow within chambers was at a higher or lower velocity than open areas depending on ambient wind speed.

This evaluation reports and discusses the magnitude of the differences in the microenvironment between chambers and open areas for studies conducted during 1976. Greatest emphasis was placed on solar radiation, temperature, air flow, and evaporation.

Procedures

Solar Radiation--

Solar-radiation reduction in the chambers was determined by measuring photosynthetic photon-flux density (PPFD) at 29 positions in one chamber at approximately hourly intervals between 8 am and 6 pm on two bright cloudless days, i.e., 2 July and 20 September 1976. A rigid aluminum angle-iron frame with four arms (each 1.1 m long) was constructed for support and easy movement of the light sensor. Positions were marked off at 15-cm intervals along each of the arms, and the frame was positioned so that the arms were directed out from the center in N, S, E, and W directions. A Lambda quantum sensor (LI-190S) measuring radiation in the spectrum beween 400 and 700 nm was attached to a wooden block and pushed along the frame from position to position with a thin pole from outside the chamber. Measurements were taken above the alfalfa canopy, 38 cm above the soil surface. The radiation intensity at the center of an open plot also was recorded at the time of each chamber measurement.

The sun angle at the time of each set of PPFD readings were determined by use of the following formulae (List 1968):

$$\sin a = \sin \phi \sin \delta + \cos \phi \cos \delta \, h \qquad (2)$$

where

a is sun angle,

ϕ is latitude,

δ is solar declination angle $= [23.45 \cos \frac{185}{182.5\,(n-175)}]$

n is day of year, and

h is hour angle of sun time from solar noon in hours x 15°.

Valid radiation readings could only be obtained on cloudless days because on partly cloudy days reflection from clouds and indistinct haze caused rapid fluctuations in radiation measurements.

Air Temperature--

Diurnal temperature differences between chambers and open plots and temperature differences in chambers were determined through use of iron-constantin #24 thermocouples shaded with aluminum foil and attached to a wooden dowel frame with four arms. Five thermocouples were attached to the frame, one at the center and the others at the ends of the arms in N, S, E, and W directions from the center. The thermocouples were positioned on the arms 0.9 m from the center of the chamber and were supported over the alfalfa 38 cm above the soil surface. The thermocouple leads extended to the outside of the chambers and were monitored with a shaded potentiometer. An additional reference thermocouple was positioned outside the chambers 38 cm above the soil over the alfalfa in the center of the experimental area. The reading on the reference thermocouple was used to correct for temperature variations that occurred over the plot area during the time that successive plots were monitored.

Temperature was monitored in one chamber once every hour between 8 am and 5:30 pm on a clear day (19 August). Temperatures were monitored in all plots in bright sunlight on 2 July at 8 am, 2 September at 12 am, 19 August at 7 pm, and during the dark on 20 September at 7 pm.

Air Flow--

Air-velocity measurements were taken in the chambers on two separate days during the course of the experiment in addition to the measurements taken in the intake ducts when the chambers were set up. The measurements in the chambers were taken late in the afternoon on days when ambient air flow was low (< 6 m/min) so that the influence of ambient air turbulence would be minimized. They were obtained with an Anemotherm Model 60 directional hot-wire anemometer. The air flow was measured 0.9 m N and 0.9 m S of the center in each plot at positions where temperature and evaporation measurements were taken.

A comparison of air velocity levels at different places in a chamber was made at 15-cm intervals across one filtered chamber just above the alfalfa canopy and 38 cm above the soil surface. Measurement positions at 15-cm intervals were marked on strings suspended across the diameter of the chamber in N-S and E-W directions. The 37 readings were taken in the chamber. Readings were taken with the anemometer attached to the end of a thin pole with the sensor attached so that the operator could remain outside the plot. Measurements were taken with the anemometer oriented to measure horizontal air flow in an E-W direction and then reattached and oriented so that it measured horizontal air flow in a N-S direction.

Evaporation--

The rates of evaporation were determined with white and black flat-top Bellani atmometers (Kahl Scientific Instrument Company). Three pairs of white and black atmometers were located in each plot. One pair was positioned at the center of the plot, and the other two pairs were positioned 0.9 m N and S of the center point at positions where temperatures were taken. Atmometers were left in the three plots of each replicate for 10 days with the bottles refilled and the quantity of added water recorded every 3 to 4 days. After three measurements were taken from each plot, the atmometers were moved to the plots of the second replicate, and a similar set of three measurements were obtained. This procedure was repeated for the third replicate. Average daily water loss for each chamber or open area was calculated. Because evaporation rates were very different over the periods of measurement for each replicate, the data for each replicate period was corrected to average water loss for the three replicate periods.

Data

Solar Radiation--

Solar radiation in chambers was shown to be nearly the same as in open areas. This similarity was caused by several factors including the uncovered open-tops of the chambers, the use of plastic for the chambers which transmitted approximately 95% of the incident radiation, and the minimum amount of radiation that was blocked by the chamber frame.

The radiation level in the chambers compared to the level in open areas varied with measurement over the day as indicated by data for radiation intensity for different sun angles (Figure 19). The radiation level in the chambers was approximately the same as open areas when the sun was low in the horizon at dawn and dusk, and when the sun was near the zenith at solar noon (70°). During the morning and afternoon when the sun angle was approximately 40°, radiation in the chambers was approximately 15% less than radiation in open areas. This small amount of reduction in radiation intensity in chambers compared to open areas would not be expected to have much effect on plants growing throughout an entire growing season.

The magnitude of decrease in radiation for chambers maintained in different areas of the country was estimated from data obtained in this study. Hourly sun angles were calculated for 20, 30, 40, and 50° latitudes for the times of solstice and equinox (21 March, 21 June, and 21 December), and the measured radiation reductions for these sun angles were used to calculate average daily radiation in chambers for these latitude locations and yearly dates (Table 35). For sun angles > 70° (the maximum angle recorded at Madison), the radiation intensity in the chambers was assumed to be the same as the radiation outside the chambers. At approximately 40° N latitude where this experiment was conducted, the average radiation per day

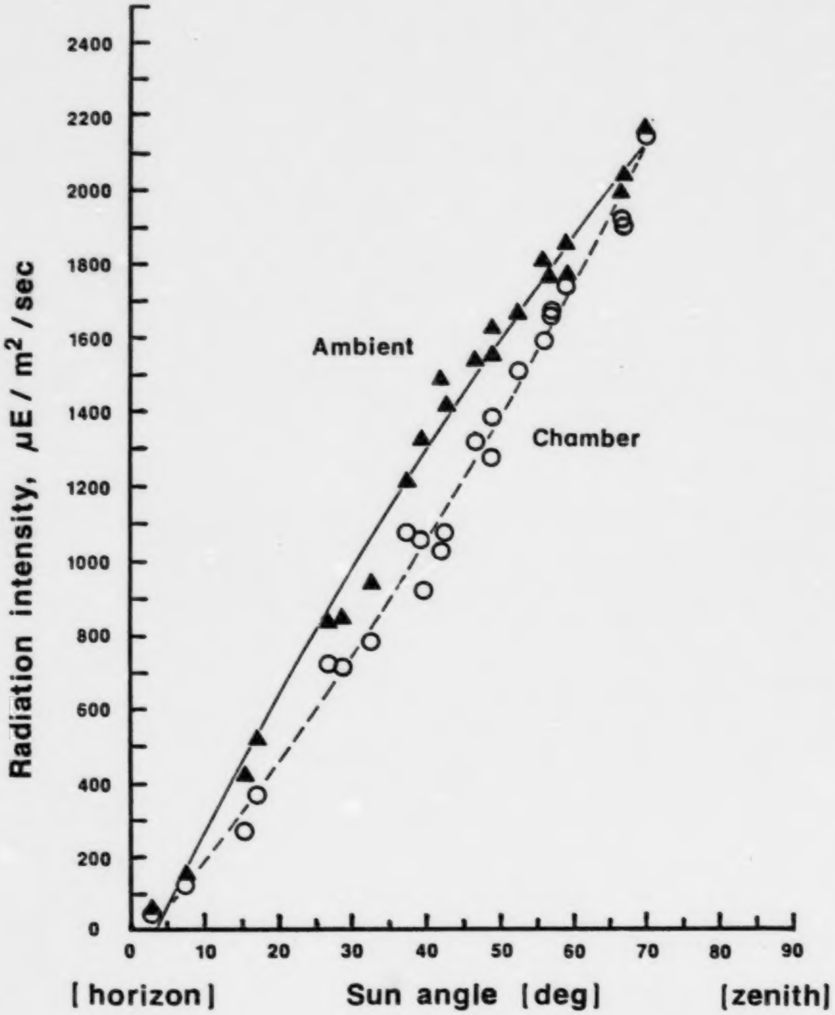


Figure 19. Radiation intensity of open-top field chambers compared to ambient areas. Chamber intensity (Y) is $Y = 53.41 + 22.94x + 0.0116x^2$. Ambient intensity (Y) is $Y = 135.30 + 40.46x - 0.116x^2$.

in chambers could be 10% less than that in open areas during the summer solstice (Table 35). At the spring and fall equinoxes (Table 35), the reduction in radiation would be 20% in chambers. If open-top field chambers are used at lower latitudes in the United States (20° or 30° latitude), the percentage of reduction in radiation received per day would be even less. Much of the crop acreage of the United States is located in these warmer areas, where, even if the chambers were used for crops growing during the winter, the percentage difference in radiation intensity in the chambers would not be large. At latitudes higher than that at Madison (43°), the reduction in radiation intensity during the growing season would not be very significant. At high latitudes the reductions in intensity are small during the middle of the growing season, and when reductions in intensity are large (during the equinoxes) temperatures are too low to permit much growth.

Radiation levels varied somewhat in different areas in the chambers depending on the angle of the incident radiation, the presence of frame crossbars in the path of the radiation, reflection from the chamber plastic, and the amount of dust on the chamber walls. Measurements taken at 1 pm CDT 2 July 1976 (Figure 20) showed that the lowest radiation intensity occurred at the S perimeter of the chamber, while the highest radiation intensity occurred near the N perimeter. Across the rest of the chamber the radiation intensity was about the same as in open areas.

The radiation-measuring system allowed for effective determination of radiation in the chambers but required a significant amount of labor to obtain data throughout the day. Continuous data could be obtained more efficiently and more accurately by attaching the sensor to an integrator to sum the radiation coming into the chamber over specified periods of time. A second sensor could be located in an open area to provide comparison data so that the average and total reduction in radiation intensity in the chambers could be determined.

Air Temperature--

The average air temperature in the chambers was approximately the same as in open areas (Table 36). Air temperatures in the chambers were slightly higher (0.5°C) early in the morning and at noon (2°C) while late in the afternoon and in the dark, the temperatures in the chambers and in the open areas were the same. These results were consistent with those of other investigators who found that temperatures in the chambers were the same except for a possible 2°C increase when solar intensity was high (Heagle et al. 1973 and 1979, Mandl et al. 1973, Heggestad et al. 1977). No significant variation in temperature was found in different areas of the chambers, except in small areas where reflection of sunlight from the inside surface of the plastic increased the air temperatures.

The temperature monitoring system was useful in characterizing temperatures in the chambers and open areas at certain times during the day, but it could not provide information concerning differences in temperature over long periods of time. The data showed that temperatures varied little between chambers or within chambers at any particular time. Therefore, one

TABLE 35. RADIATION* CALCULATED FOR OPEN-TOP FIELD CHAMBERS AT DIFFERENT LATITUDES AT THE TIMES OF SOLSTICE AND EQUINOX

	Summer solstice (21 June)			Fall and spring equinox (21 September and 21 March)			Winter solstice (21 December)		
Latitude	Opens areas	Chamber	Reduction (%)	Open areas	Chamber	Reduction (%)	Open areas	Chamber	Reduction (%)
20°	6.48	5.91	8.8	5.38	4.76	11.4	4.60	3.74	18.8
30°	6.71	6.25	6.8	4.83	4.09	15.3	2.62	1.99	24.0
40°	6.62	6.27	10.3	3.48	3.29	19.5	1.68	1.24	26.6
50°	6.39	5.50	13.8	3.28	2.53	23.1	0.81	0.58	27.8

*10^7 µE/m^2/day for 400 to 700 nm.
†Reduction of radiation in chambers.

TABLE 36. AVERAGE TEMPERATURES* (°C) AT FOUR SELECTED TIMES IN FILTERED CHAMBERS, NON-FILTERED CHAMBERS, AND OPEN AREAS

Treatments	Time			
	7:00 am	12:00 am	5:45 pm	7:00 pm
Filtered chambers	14.3 ± 0.3y†	23.9 ± 0.6y	27.8 ± 1.2y	11.6 ± 0.2y
Non-filtered chambers	14.2 ± 0.3y	23.9 ± 0.6y	27.8 ± 1.2y	11.6 ± 0.2y
Open areas	13.7 ± 0.2z	21.9 ± 0.4z	27.9 ± 0.6y	11.6 ± 0.3y

*Treatment mean temperature at any time is an average of 15 temperatures, five from each of three replicates.

†Treatment means in a column followed by the same letter are significantly different at the 95% level.

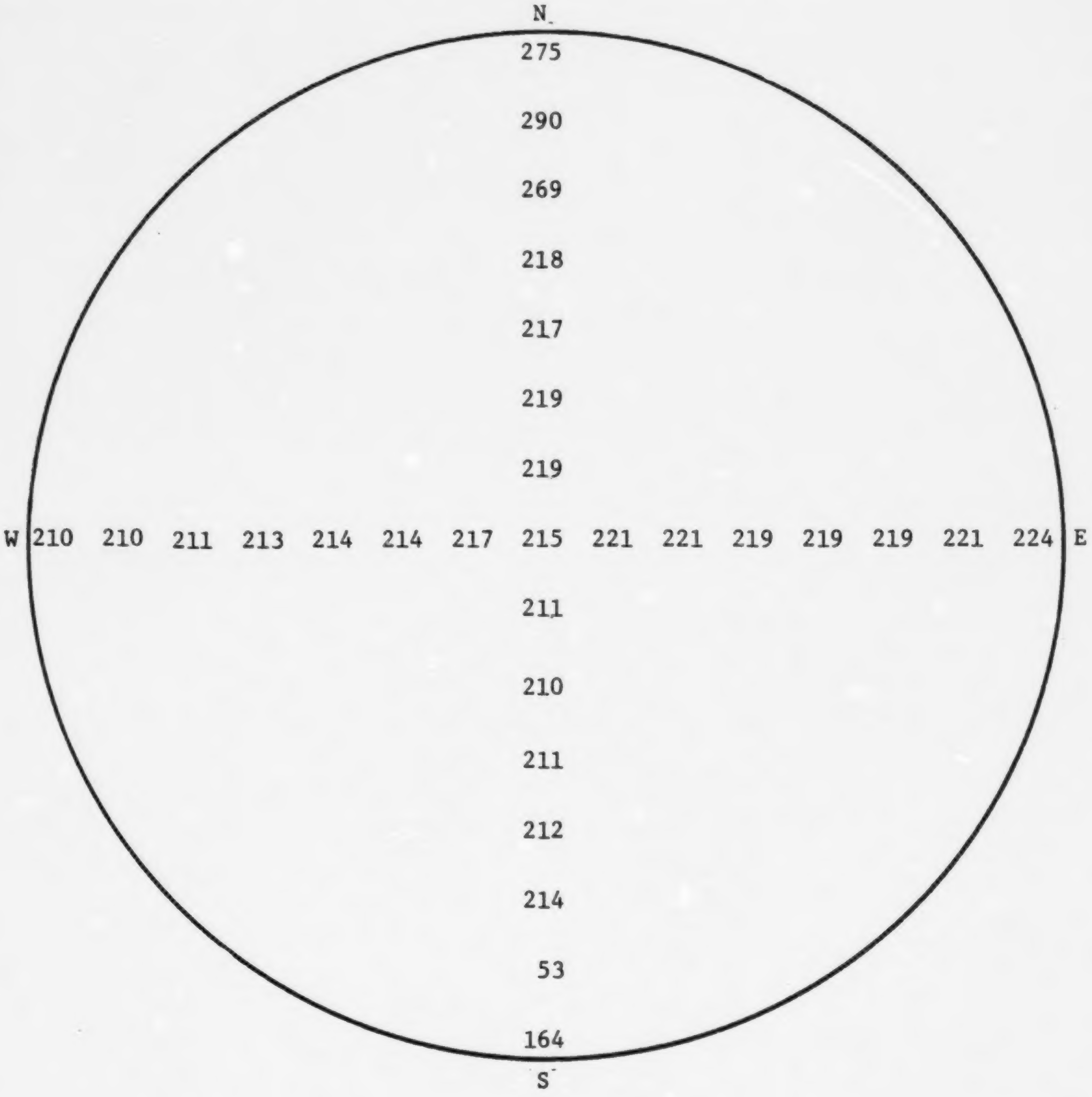

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Figure 20. Radiation intensity (NE cm^{-2} S^{-1} for 400 to 700 nm) at 15 cm intervals across open-top field chamber at 1300 CDT, 2 July 1976.

thermocouple carefully located within a chamber could be used to monitor chamber temperature. If a single thermocouple were used, it could be attached to a potentiometer and recorder to monitor temperature continuously. A second thermocouple could be positioned in an open area and its temperature monitored continuously. Comparison of data from the two thermocouples would provide a precise record of temperature differences between chambers and open areas over an extended period.

Air Flow--

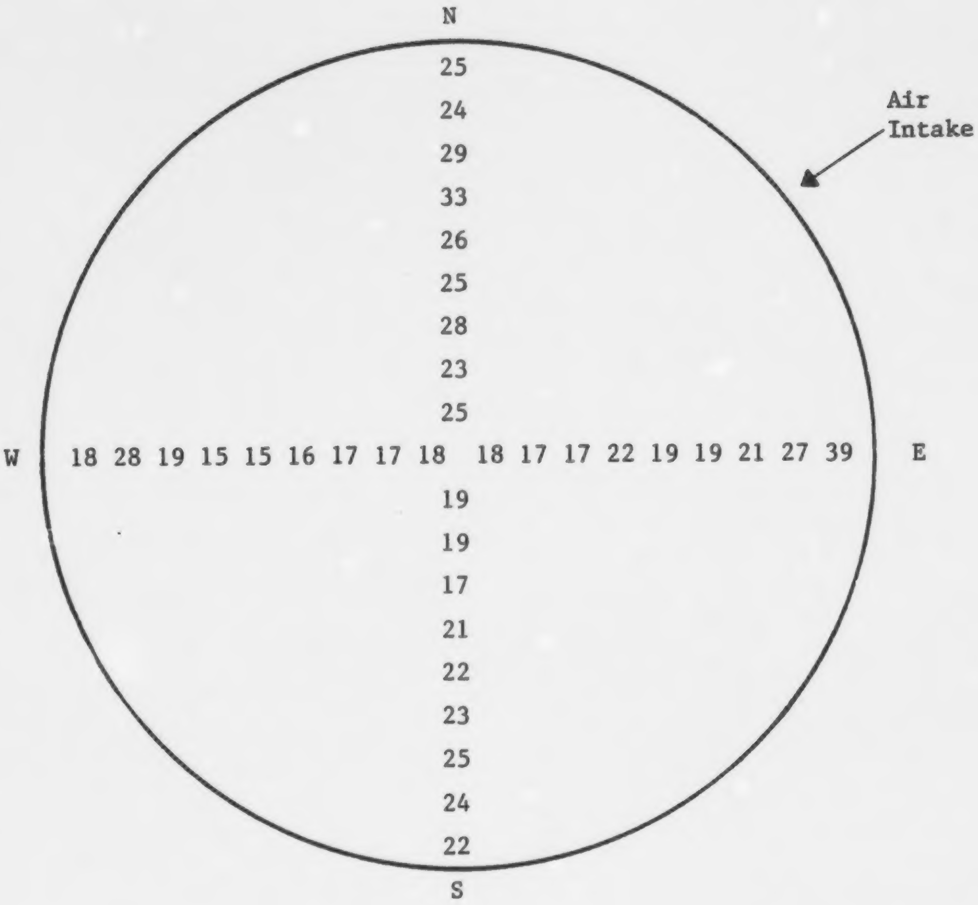
Air flow in the chambers was controlled by the velocity of the air forced into the chambers by the blower and the velocity of air entering through the open top (Heggestad et al. 1977). When ambient air velocity was low, the average air velocity through the chambers was constant. During periods with gusty ambient winds, air enters the top of the chamber and causes greater variation in air velocities over the plants (Heagle et al. 1973, Heggestad et al. 1977). Air velocity across the chambers was uniform ranging from 10 to 30 m/min (Figure 21). Air flow was highest near the air holes at the perimeter of the chamber and lowest near the center of the chamber; however, the differences over most of the chamber area were not large.

The air velocity monitoring system provided for effective measurement of horizontal air flow across the chambers and between filtered and non-filtered chambers. Measurement of vertical air flow at different heights in a representative chamber were desirable to characterize the amount of polluted ambient air entering the open top of the chamber with different ambient wind velocities (Heagle et al. 1973). This measurement is important because, as indicated earlier, turbulent mixing of ambient air with chamber air can cause significant changes in pollutant levels in the filtered chambers.

Evaporation--

Differences in evaporation between chambers and open areas were recorded (Table 37), with black- and white-bulb Bellani atmometers. Open areas had higher evaporation (15 ml/day black atmometer and 11 ml/day white atmometer), than the chambers (13 ml/day black atmometer and 10 ml/day white atmometer). As a result, plants in open areas probably transpired more and had less available moisture for plant growth. These plants would have been under greater water stress, which might reduce their sensitivity to pollutants compared to plants growing in the chambers. Differences in evaporation were also found between areas in the chambers (Table 38). The N quadrat had a greater water loss than the center or S quadrats, as indicated by black and white atmometer measurements. The result may have been caused by greater radiation intensity at this position.

The evaporative losses in chambers and open areas provided an indication of the relative amount of water stress that plants were subjected to in these different areas. The evaporation from atmometers, however, is not directly proportional to transpiration from plants and therefore must be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Air Intake

Figure 21. Air flow (m min^{-1}) at 15 cm intervals across open-top field chamber. Readings shown are with sensor orientation in the direction of each of the transects across the chamber.

TABLE 37. AVERAGE DAILY WATER LOSS (ML/DAY) FOR BLACK AND WHITE ATMOMETERS LOCATED IN FILTERED CHAMBERS, NON-FILTERED CHAMBERS, AND OPEN AREAS

Treatment	Water loss	
	Black atmometer	White atmometer
Filtered chambers	13.9 ± 1.1y*	9.6 ± 0.7x
Non-filtered chambers	12.8 ± 1.3x	9.6 ± 0.5x
Open areas	14.8 ± 0.8z	10.5 ± 0.8y

*Treatment means in a column followed by the same letter are significantly different at the 95% level.

TABLE 38. AVERAGE DAILY WATER LOSS (ML/DAY) FOR BLACK AND WHITE ATMOMETERS IN SEPARATE AREAS OF FILTERED AND NON-FILTERED CHAMBERS

	Water loss	
Chamber area	Black atmometer	White atmometer
North	14.6 ± 0.7z*	10.1 ± 0.4y
Center	13.2 ± 0.8y	9.5 ± 0.3y
South	12.2 ± 0.9y	9.2 ± 0.6y

*Treatment means in a column followed by the same letter are significantly different at the 95% level.

utilized only for qualitative estimates of plant water stress. This is because atmometer evaporation is controlled by the boundary-layer resistance to water vapor at the evaporating surface of the atmometer; while plant transpiration is controlled by the boundary-layer resistance and the stomatal resistance of leaves.

SECTION 8

CONTROLLED EXPOSURES OF FIELD CROPS TO AIR POLLUTANTS

INTRODUCTION

To supplement the field studies conducted near the Columbia Generating Station and to provide additional information on the effects of airborne pollutants from the generating station on local plants, several species commonly grown in the vicinity of the station (mint, *Mentha piperita* L. and *M. spicata* L.; peas, *Pisum sativum* L.; carrots, *Daucus carota* L.; beans, *Phaseolus vulgaris* L.; and alfalfa, *Medicago sativa* L.) were exposed under controlled laboratory conditions to appropriate air pollutants. The studies were directed toward (1) determining which species are sensitive to air-pollutant damage, (2) identifying the symptoms of pollutant injury associated with each of these species, and (3) measuring the sensitivity of different cultivars of each species. These objectives were chosen because of their importance in assessing the amount of damage to a crop and in recommending certain cultivars for planting to prevent or minimize air-pollutant injury.

Peas, alfalfa, carrots, and beans are known to be sensitive to sulfur dioxide (SO_2), (U.S. Environmental Protection Agency 1973, Applied Science Associates, Inc. 1978), and peas and beans are known to be sensitive to ozone (O_3), (U.S. Department of Health, Education and Welfare 1970, U.S. Environmental Protection Agency 1973, Ormrod 1976). Carrots are moderately sensitive to ozone (Bennett and Oshima 1976). Mint is resistant to SO_2 (Hill et al. 1961) and O_3 (Runeckles and Rosen 1974).

The two gases used in the controlled exposures were SO_2 and O_3. Sulfur dioxide is the major phytotoxic pollutant emitted from the Columbia Generating Station. Ozone is present in ambient air in the area of this station in concentrations high enough to cause damage to susceptible species (Table 14). These gases also were combined in exposures on the plants since O_3 is expected to be present in the atmosphere with the SO_2 emissions from the station. The combined exposures are of particular interest because combined pollutants often have caused more injury than separate pollutants (Menzer and Heggestad 1966, Tingey et al. 1971, Costonis 1973, Reinert and Gray 1977).

PROCEDURES

Growing Conditions

To insure uniformity in response to pollutants, plants were grown in controlled-environment rooms at the Biotron of the University of Wisconsin-Madison. All species were maintained at 20 ± 1°C (measured with thermocouples), 70 ± 5% relative humidity (measured with wet- and dry-bulb psychrometers), and an air flow of about 12 m/min over the plants (measured with an Anemotherm Model 60 hot-wire anemometer). Cool-white fluorescent and incandescent lamps provided a quantum flux density of 325 ± 10 micro Einsteins (400 to 700 nm) as measured with a Lambda LI-185 light meter. Cultivars of peas, carrots, beans, and alfalfa were grown from seed, and the mint cultivars were propagated vegetatively from rhizomes (underground stems). All plants were grown in a commercial peat-vermiculite mixture, watered to excess with a modified Hoagland's solution four times daily with an automatic watering system, grown under a 16:8 LD photoperiod, and thinned and staked as necessary. These growing conditions produced succulent, pollutant-sensitive plant material.

Exposure Conditions

Two plexiglass chambers were used in the experiments. In one chamber plants were exposed to pollutants and in the control chamber plants were maintained in filtered "clean" air. Environmental conditions during exposure to pollutants were maintained at approximately the same levels that the plants had been grown.

Sulfur dioxide was obtained by controlled metering of 0.1 ppm (260 $\mu g/m^3$) SO_2 in N_2 from a pressurized tank into the chamber air-handling system. This pollutant was monitored during initial exposures with a Scientific Industries Model No. 60 analyzer, with a Meloy SO_2 analyzer using a flame-ionization procedure, and, in later studies, with a ThermoElectron Company Model No. 43 pulsed fluorescent analyzer.

The O_3 concentrations were maintained by regulating the electric current to ultraviolet lamps in the intake air ducts. Ozone was measured during the fumigations in early studies with Mast oxidant meters, and in later studies with a Monitor Laboratories 8410A Chemiluminescent O_3 meter. All analysers were carefully calibrated with a Monitor Laboratory Permacal and at times with a Bendix 8861 Gas Phase titrator. The calibrators were calibrated regularly at the Wisconsin Air Chemistry Laboratory according to U.S. Environmental Protection Agency guidelines.

Beans were fumigated at 11 or 12 days after planting, peas after 11 or 13 days, alfalfa after 21 days, and carrots after 35 days. Mint was fumigated 35 days after planting the rhizomes.

Exposures were conducted at many different concentrations of SO_2 and O_3 for differing lengths of time. All plants were exposed to pollutants during the first 2 to 10 h of the 16-h light period, when they were most sensitive to pollutants. Exact conditions are reported with the experimental data.

Injury-Scoring Procedure

Injury data were taken 4 days after exposure for beans and 7 days after for peas, alfalfa, carrots, and mint. The percentage of injury for beans, alfalfa, carrots, and mint was determined by visual estimation of the extent of leaf area injured. Injury for peas was determined by measurement of the necrotic area of one leaflet from each leaf. The leaflet was placed on 3 mm graph paper onto which the outlines of the total leaflet and injured areas were traced. The area of injury was determined by counting the number of graph squares in the traced areas. The total leaflet area was determined with a Hayashi-Denko Model AAM-5 automatic area meter. The percentage of leaf area injured was calculated by dividing the injured area by total area for each leaflet.

Injury data were taken from the leaves that were found to be the most sensitive on each of the different crop species: peas--first and second true leaf above the cotyledons; beans--unifoliate leaves; carrots--third true leaf above the cotyledons; alfalfa--first, second, and third trifoliate leaves above the cotyledons; mint--leaves from the middle third of the plant.

In addition to visual estimates or measurements of injured leaf area, leaf-chlorophyll content was determined in certain studies with peas, beans, and alfalfa using procedures developed by Knudson et al. (1977). This procedure involved extractions of chlorophyll with 100% ethanol. The chlorophyll concentration of a leaf was expressed as μg chlorophyll/mg dry weight. The percentage reduction in chlorophyll concentration of treated leaves compared to the chlorophyll concentration of untreated leaves of control plants was determined.

Experimental Design

Peas--

Relative sensitivity of two pea cultivars to SO_2 was determined by exposure of four plants of each cultivar to 0.65 ppm SO_2* for 2 h. Relative sensitivity of pea cultivars to O_3 was determined by exposing four plants each of 14 pea cultivars to 0.25 ppm O_3 for 2 h.

Determinations of injury-threshold concentrations were made using the sensitive cultivar Alsweet. Plants were exposed to SO_2 at concentrations of

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*All pollutant concentrations in this section are in ppm taken directly from readings on the analyzer. The approximate concentration for SO_2 is 1 ppm = 2,600 μg/m^3 and for O_3 is 1 ppm = 2,000 μg/m^3.

0.4, 1.2, 1.5 and 1.7 ppm for 2, 4, or 8 h in separate exposures. Plants were exposed to O_3 at concentrations of 0.13, 0.17, 0.22, and 0.27 ppm for 2, 4, or 8 h in separate exposures. Six exposed and six control plants were used for each trial, and injury was recorded as the percentage of leaf area injured and the percentage of chlorophyll reduced. Pea plants also were exposed to 21 combinations of O_3 and SO_2 with concentrations of O_3 from 0.04 to 0.20 ppm and with concentrations of SO_2 from 0.04 to 1.23 ppm for 2, 4, or 8 h. Six or more plants were exposed to each dose combination. Injury was recorded both as the percentage of chlorophyll reduction and as percentage of leaf area injured for the first two leaves on the plants.

Carrots--

Relative sensitivity of carrot cultivars to SO_2 and O_3 injury and threshold concentrations of these pollutants were determined in a series of experiments. Four plants each of four carrot cultivars were exposed to SO_2 at four levels from 0.23 to 0.86 ppm and to O_3 at five levels from 0.12 to 0.74 ppm. The four cultivars also were exposed to three combinations of SO_2 with O_3, at concentrations of 0.23 to 0.47 ppm SO_2 and 0.15 to 0.23 ppm O_3. All exposures were for 2 h. Injury was recorded as the percentage of leaf area injured for all plants.

Mint--

Relative sensitivity of mint cultivars to SO_2 and O_3 and injury-threshold concentrations of these pollutants were determined in a series of experiments. Four plants each of three cultivars of mint were exposed to SO_2 at five concentrations from 0.20 to 1.4 ppm and to O_3 at nine concentrations from 0.28 to 1.60 ppm. All exposures were for 2 h. Four plants each of the three cultivars also were exposed to four combinations of SO_2 with O_3 at concentrations of 0.29 to 1.1 ppm SO_2 and 0.28 to 0.36 ppm O_3. Again, all exposures were for 2 h. Injury in all trials was recorded as the percentage of leaf area injured for all plants.

Beans--

Relative sensitivity of bean cultivars to SO_2 was not determined; only a single cultivar was evaluated in SO_2 exposures. Relative sensitivity of bean cultivars to O_3 was determined by exposing plants of 20 cultivars to 1.47 ppm O_3 for 1 h. Each cultivar was exposed to O_3 in two trials of four plants each. To provide a check on uniformity of exposure conditions, two plants each of the 'Pinto' cultivar also were exposed with each exposure of other cultivars. Injury was determined using percentage of chlorophyll reduction and percentage of visual leaf injury. To determine if cultivars were of similar sensitivity under short and long duration exposures, four or more plants of each of two sensitive and two resistant bean cultivars selected from previous experiments were exposed to O_3 at 1.37 ppm for 1 h, 0.64 ppm for 2 h, or 0.25 ppm for 8 h. To determine injury-threshold concentrations for SO_2, plants of the cultivar 'Tenderette' were exposed to 1.75, 2.75, and 3.50 ppm SO_2 for 1 h and threshold concentrations of O_3 were obtained for this same cultivar with exposures of 0.1, 0.2, and

0.3 ppm O_3 for 1 h. Six treated plants were compared with six control plants at each concentration. Tenderette plants also were exposed to SO_2 and O_3 in combination, at concentrations of 0.08 ppm SO_2 plus 0.08 ppm O_3 and 0.2 ppm SO_2 plus 0.08 ppm O_3. The 12 treated plants were compared with 12 control plants for each concentration. Injury was estimated by the percentage of chlorophyll reduction and by the percentage of visible leaf injury.

Alfalfa--

To determine relative sensitivity of alfalfa to SO_2, six plants each of five alfalfa cultivars were exposed to 1.35 ppm SO_2 for 4 h. Injury threshold levels were determined for the alfalfa cultivar 'Vernal' (commonly grown in the station area) with SO_2 and O_3 alone and in combination. Ten plants were exposed for 4 h to four levels of SO_2 (0.70 to 1.35 ppm) in one series of exposures and to five levels of O_3 (0.13 to 0.36 ppm) in another series of exposures. Nine plants were exposed to a combination of four levels of SO_2 (0.25 to 0.69 ppm) and 0.13 ppm O_3 for 4 h. All treated plants were compared with an equal number of control plants. Injury was determined by the percentage of chlorophyll reduction and by the percentage of visible leaf injury in both experiments.

Statistical Analysis

Statistical analyses of data were carried out using standard ANOVA and Duncan's New Multiple-Range Test (Steel and Torrie 1960). The procedures used are noted in the results section for each species.

RESULTS AND DISCUSSION

The results of controlled exposures for all crop plants are summarized together. The description of injury symptoms from SO_2 and O_3 for each species is provided in Table 39. The relative sensitivity of locally-grown cultivars of the five crop species in ranked order are given in Table 40. The minimum levels of SO_2 and O_3 required to produce injury symptoms on plants of the most sensitive cultivar of each of the five species exposed to the gases separately or in combination are given in Table 41.

Peas

Peas previously have been estimated to be intermediate in sensitivity to oxidants (U.S. Environmental Protection Agency 1973) and sensitive to SO_2 (U.S. Department of Health, Education and Welfare 1970). Previous experiments, however, have used cultivars that are not commonly grown in Wisconsin. Injury from SO_2 exposure in this study developed at concentrations at or above 1.25 ppm for 2 h and appeared as well-defined interveinal bleaching of the leaf tissue on upper and lower leaf surfaces. In a 5-day period the tips of the lobes showed tissue collapse, turned brown, and then turned a bleached white. Injury due to O_3 developed at

TABLE 39. CHARACTERISTIC INJURY SYMPTOMS ON CROP PLANT LEAVES FOLLOWING EXPOSURE TO SO_2, O_3, AND SO_2 PLUS O_3

Pollutant	Crop				
	Peas	Carrots	Mint	Beans	Alfalfa
SO_2	Large, well defined, interveinal bleached areas. Leaves may become chlorotic. No associated flecking. Most serious on oldest leaves.	No injury found at concentrations tested.	Large, well defined, interveinal bleached areas. No associated chlorosis or flecking. Most serious on middle-aged leaves.	Large, discrete necrotic and/or chlorotic spots on upper leaf surfaces, especially near margins.	Necrosis along leaf margins; more near tips. Occasionally accompanied by chlorotic mottling. At very low levels, pinpoint flecking along veins. Most serious on middle-aged leaves.
O_3	White flecking over whole leaf or concentrated at margins. Margins become necrotic, whole leaf chlorotic. Oldest leaves injured most. Leaves senesce at high concentrations.	Brown flecking most serious at tips of leaf lobes. Leaves may become chlorotic with tips necrotic. Most serious on middle-aged leaves.	White flecking over entire leaf or concentrated at margins. Most serious on middle-aged leaves.	Necrotic flecking of adaxial leaf surfaces, also pigmented lesions and chlorosis of adaxial surfaces. Field injury often accompanied by bronzing of leaves. Some differences in symptoms depending on cultivar.	Necrosis along leaf margins; more near tips. Necrosis extending into leaf lamina somewhat, often as flecking. Old and middle-aged leaves affected more than young leaves.
SO_2 + O_3	Large marginal necrotic areas. A combination of both SO_2 and O_3 symptoms. Most serious on oldest leaves.	Necrotic die-back of leaf tips. Lower leaf surfaces gray-white. Most serious on middle-aged leaves.	Leaves become very necrotic with a combination of SO_2 and O_3 symptoms. Leaves often twisted, curled, and chlorotic. Most serious on middle-aged leaves.	No injury found at concentrations tested.	Combination of SO_2 and O_3 symptoms, more closely resembling O_3 injury.

TABLE 40. RELATIVE SENSITIVITY OF CROP CULTIVARS TO SO_2, O_3, AND SO_2 PLUS O_3*

Pollutant	Crop				
	Peas	Carrots	Mint	Beans	Alfalfa
SO_2	Alsweet New Line Early Perfection	Carousel= Danvers= Scarlet Nantes= Royal Core Chantenay	Black Mitcham Peppermint Common Spearmint= Todd Mitcham Peppermint		Vernal= Agate= Apollo= Iroquois= Saranac
O_3	Alsweet= Green Arrow Davis Perfection Alaska Delwich Commando New Era New Line Early Perfection= Wando Sprite New Season Dark Skin Perfection New Wales= Wisconsin Perfection Dwarf Grey Sugar	Royal Core Chantenay Danvers Carousel Scarlet Nantes	Common Spearmint Black Mitchum Peppermint Todd Mitcham Peppermint	Sanilac Tenderette Blue Lake Stringless= Buch Blue Lake 290 Spurt Apollo Early Gallatin= Pinto= Bush Blue Lake 274= Bush Blue Lake 53 Cascade Coloma Provider Tendergreen= Orbit Resistant Asgrow Valentine Tempo Ford Hook 242 Black Turtle Soup French's Horticultural	
SO_2 + O_3		Carousel Scarlet Nantes Royal Core Chantenay Danvers	Black Mitcham Peppermint Common Spearmint Todd Mitcham Peppermint		

*Cultivars are listed in order of sensitivity, with the most sensitive at the top of each list. Cultivars followed by = are equivalent in sensitivity to the following cultivar.

TABLE 41. MINIMUM CONCENTRATIONS OF SO_2, O_3, AND SO_2 PLUS O_3 (PPM)*
CAUSING VISIBLE INJURY TO CROPS IN CONTROLLED EXPOSURES

Pollutant	Crops				
	Peas	Carrots	Mint	Beans	Alfalfa
SO_2	1.23 for 2 h	No injury at 0.85 for 2 h	1.40 ppm for 2 h	2.75 ppm for 4 h	1.00 ppm for 1 h
O_3	0.13 ppm for 8 h	0.44 ppm for 2 h	0.50 ppm for 2 h	0.40 ppm for 4 h	0.25 ppm for 1 h
SO_2+O_3	0.11 + 0.06 for 4 h	0.57 ppm + 0.15 ppm for 2 h	0.44 ppm + 0.47 ppm for 2 h	No injury at 0.20 ppm + 0.08 ppm for 4 h	0.26 ppm + 0.13 ppm for 4 h

*1 ppm $SO_2 \simeq 2,600\ \mu g/m^3$; 1 ppm $O_3 \simeq 2,000\ \mu g/m^3$.

concentrations at or above 0.22 ppm for 2 h and was evident as a diffuse flecking of the leaves on the upper surface only; the flecks occasionally were more concentrated at the tips of the leaf lobes. Senescence of severely injured leaves from plants exposed to O_3 or combinations of SO_2 and O_3 often occurred from 4 to 7 days after treatment. Mixtures of gases with O_3 at 0.15 ppm and $SO_2 > 0.10$ ppm produced injury symptoms characteristic of individual gases. Table 39 summarizes the injury symptoms for the studies, symptoms which generally occurred first and most seriously on fully expanded leaves (from individual or combined gases). Only the first and second leaves were fully-expanded on the pea plants at time of exposure.

Of the 14 cultivars tested, 'Alsweet' and 'Green Arrow' appeared to be the most sensitive to O_3 (Table 40, Table 42), but the differences between cultivars were small and are likely to have little practical significance.

Alsweet was chosen for detailed study since it was more sensitive than most other cultivars tested. Results of exposures with SO_2 to determine minimum concentrations for injury (Table 43) indicated that the minimum threshold was 1.25 ppm. This level caused a little over 10% reduction in chlorophyll content and a trace of leaf injury at 2-, 4-, and 8-h exposures. Increasing the concentration to 1.50 and 1.75 ppm increased visible leaf injury and loss of chlorophyll. Data on injury determined by loss of chlorophyll showed a more consistent increase in injury with increasing exposure time and with increasing concentration than the data on injury determined by visual estimates.

Results of exposures of Alsweet peas to O_3 (Table 44) indicated that at 0.22 ppm an exposure of at least 2 h was needed to cause significant injury. The lack of significant injury with exposure to 0.17 ppm O_3 for periods as long as 8 h indicated a sharp threshold for injury. Chlorophyll reductions were proportional to leaf area injured for the second true leaf. Visible injury and chlorophyll reductions were less for the first and third leaves than for the second leaf.

The results indicate that concentration may be more important than exposure duration in determining minimum threshold for injury caused by both pollutants. The results also indicate that the maximum concentrations of 0.15 ppm SO_2 for 1 h or 0.13 ppm O_3 for 1 h that have been measured in the Columbia Generating Station area are not--of themselves--high enough to cause visible injury to peas.

When plants were exposed to O_3 and SO_2 concurrently, a greater than additive effect on leaf injury was demonstrated (Table 41, Table 45). In 2-h exposures a level of $SO_2 > 0.10$ ppm coupled with 0.17 ppm O_3 can have a greater than additive injury effect on peas, and in 4-h exposures such an effect can occur with an SO_2 level > 0.10 ppm and an O_3 level of 0.13 ppm. If the maximum measured concentrations of O_3 and SO_2 in the Columbia Generating Station area were to occur concurrently, then some damage to peas might result. Such occurrences are rare (section 3), and thus the chance is remote that these combined high levels would occur during daylight hours and

TABLE 42. RELATIVE SENSITIVITY OF PEA CULTIVARS TO O_3

Cultivars	Visible injury (%)†
Alsweet	9.5
Green Arrow	9.5
Davis Perfection	6.0
Alaska	5.5
Delwich Commando	5.0
New Era	4.5
New Line Early Perfection	3.5
Wando	3.5
Sprite	3.5
New Season	3.0
Dark Skin Perfection	1.5
New Wales	1.0
Wisconsin Perfection	1.0
Dwarf Gray Sugar	0.5

*Pea plants were exposed to 0.25 ppm O_3 for 2 h.

†Average amount of flecking and necrosis for first and second true leaves (third and fourth nodes above the cotyledon) of four plants.

TABLE 43. DOSAGE RESPONSE OF ALSWEET PEAS EXPOSED TO SO_2*

Concentration (ppm)†	Time of exposure (h)	Leaf area injured (%)	Chlorophyll reduction (%)
1.72	8	67	76
1.50	8	46	44
1.23	8	2	9
0.42	8	0	-8
1.72	4	38	44
1.50	4	25	42
1.23	4	(tr)‡	18
0.42	4	0	0
1.72	2	16	23
1.50	2	31	19
1.23	2	(tr)	11
0.42	2	0	-1

*Data for second true leaf from six exposed and six control plants.

†1 ppm SO_2 ≈ 2,600 μg/m^3; 1 ppm O_3 ≈ 2,000 μg/m^3.

‡(tr) indicates a trace of injury. No more than 5% leaf area injured on any one plant.

TABLE 44. DOSAGE RESPONSE OF ALSWEET PEAS EXPOSED TO O_3*

Concentration (ppm)†	Time of exposure (h)	Leaf area injured (%)	Chlorophyll reduction (%)
0.27	8	89	71
0.22	8	78	78
0.17	8	5	10
0.13	8	(tr)‡	21
0.27	4	72	61
0.22	4	84	65
0.17	4	(tr)	8
0.13	4	0	10
0.27	2	36	25
0.22	2	33	26
0.17	2	(tr)	1
0.13	2	0	4

*Data for second true leaf from six exposed and six control plants.

†1 ppm SO_2 ≈ 2,600 μg/m^3; 1 ppm O_3 ≈ 2,000 μg/m^3.

‡(tr) indicates a trace of injury. No more than 5% leaf area injured on any one plant.

TABLE 45. DOSAGE RESPONSE OF ALSWEET PEAS EXPOSED TO SO_2 PLUS O_3*

Pollutant		Length of exposure (h)	No. of plants exposed	Leaf area injured (%)
SO_2† (ppm)	O_3† (ppm)			
1.23	0.13	8	6	87
0.11	0.06	4	12	(tr)‡
0.11	0.11	4	12	6
0.11	0.13	4	18	16
0.14	0.13	4	6	26
0.18	0.13	4	6	44
0.40	0.13	4	12	32
1.23	0.13	4	6	55
0.42	0.04	2	6	0
0.42	0.13	2	6	63
1.23	0.13	2	6	48
0.05	0.17	2	12	10
0.10	0.17	2	6	17
0.20	0.17	2	6	17
0.24	0.17	2	6	40
0.41	0.17	2	6	49
0.42	0.17	2	12	41
0.85	0.17	2	6	82
0.96	0.17	2	6	88
1.11	0.17	2	6	89
0.42	0.20	2	6	81

*Data for second true leaf.

†1 ppm $SO_2 \simeq 2,600\ \mu g/m^3$; 1 ppm $O_3 \simeq 2,000\ \mu g/m^3$.

‡(tr) indicates at least a trace of injury. No more than 5% leaf injury to any one plant.

during the pea-growing season of April through July when plants are pollutant sensitive.

Carrots

Differences in cultivar sensitivity and injury-threshold levels for carrots exposed to SO_2 and O_3 are shown in Table 46. All four carrot cultivars studied were resistant to injury from SO_2 at the highest concentration used in these experiments (0.86 ppm for 2 h). Exposure of plants to O_3 indicated that a concentration of 0.40 ppm for 2 h may be needed to produce significant injury. Concentrations as low as 0.17 ppm for 2 h, however, did cause a trace of injury to all but 'Scarlet Nantes' carrots. Injury symptoms from O_3 consisted of brown flecking at the tips of leaf lobes with occasional chlorosis of the whole leaf. The sensitivity of cultivars appeared to vary: Scarlet Nantes and 'Carousel' showed little or no injury in response to O_3 exposure at concentrations which did produce injury to 'Royal Core Chantenay' and 'Danvers'.

When carrots were exposed to a non-injurious SO_2 concentration (0.57 ppm) in combination with a slightly injurious O_3 concentration (0.15 ppm), significant leaf injury was noted for three of the four cultivars evaluated (all except Danvers). The symptoms on the upper leaf surfaces produced by this combination of pollutants were similar to symptoms produced by O_3 alone, although the lower leaf surfaces exhibited a glazed or shiny gray-white appearance that was not seen on plants treated with SO_2 or O_3 alone.

The third leaf of carrots was used for data collection because it appeared to be the most sensitive to pollutant injury. Plants commonly had seven leaves at the time of recording of the injury (1 week after exposure) and had injury on the third through sixth leaves.

Mint

The injury to common spearmint and two cultivars of peppermint--'Todd Mitcham' and 'Black Mitcham'--with exposures to SO_2, O_3, and combinations of gases are shown in Table 47. Sulfur dioxide concentrations $\geq$ 0.70 ppm for 2 h produced well-defined collapsed interveinal areas. In spearmint these areas became brown and then turned white, but on the two peppermint cultivars the injured areas usually remained brown. All mint cultivars were moderately resistant to SO_2. No previous reports on sensitivity of mint to SO_2 are known to the authors.

Exposures of mint to 0.50 ppm O_3 for 2 h induced diffuse flecking on the leaves (Table 47). This injury was concentrated toward the apices of the leaves at lower concentrations and over the entire surface at higher concentrations. Although Ledbetter (1959) reported mint to be resistant to injury from O_3, results described herein suggest that it is moderately resistant.

TABLE 46. DOSAGE RESPONSE OF CARROT CULTIVARS EXPOSED TO SO_2, O_3, AND SO_2 PLUS O_3 FOR 2 h[*]

Pollutant		Cultivars			
SO_2[†] (ppm)	O_3[†] (ppm)	Danvers	Scarlet Nantes	Royal Chantenay	Carousel
0.23	—	0[‡]	0	0	0
0.37	—	0	0	0	0
0.40	—	0	0	0	0
0.86	—	0	0	0	0
—	0.12	1	0	0	1
—	0.17	0	0	0	0
—	0.19	1	0	1	0
—	0.22	0	0	0	0
—	0.44	11	0	21	0
0.23	0.23	1	5	1	13
0.42	0.16	0	0	0	1
0.57	0.15	0	2	4	11

[*] Data are injury estimates for third leaf averaged for four plants at each trial.

[†] 1 ppm SO_5 ≃ 2,600 $\mu g/m^3$; 1 ppm O_3 ≃ 2,000 $\mu g/m^3$.

[‡] Figures show the percentage of leaf area injured.

TABLE 47. DOSAGE RESPONSE OF MINT CULTIVARS EXPOSED TO SO_2, O_3, AND SO_2 PLUS O_3 FOR 2 h[*]

Pollutant		Cultivars		
SO_2 (ppm)[†]	O_3 (ppm)[†]	Common spearmint	Black Mitchum peppermint	Todd Mitchum peppermint
0.20	--	--	--	0[‡]
0.29	--	0	0	0
0.41	--	0	0	0
0.70	--	1	0	0
1.40	--	1	4	1
--	0.28	0	0	0
--	0.30	0	0	0
--	0.34	0	0	0
--	0.38	0	0	0
--	0.50	11	6	2
--	0.52	11	4	1
--	0.55	5	0	0
--	0.75	20	0	4
--	1.60	37	51	27
0.29	0.28	0	0	0
0.44	0.47	5	5	1
0.71	0.51	15	20	5
1.12	0.36	22	66	20

[*] Data for leaves of middle third of plants, averaged for four plants.
[†] 1 ppm $SO_2 \simeq 2{,}600\ \mu g/m^3$; 1 ppm $O_3 \simeq 2{,}000\ \mu g/m^3$.
[‡] Figures show percentage of leaf area injured.

Black Mitcham peppermint appears to be the most sensitive of the three strains tested, while Todd Mitcham is the least sensitive to SO_2, O_3, and combinations of the gases.

A combination of gases produced an inward rolling of the margins and a curling of the entire mint leaves with large necrotic areas scattered through the interveinal areas. This injury occurred with high concentrations of SO_2 and O_3 in combination. The lower (oldest) leaves of the mint plants showed the greatest amount of injury, and the upper (youngest) leaves showed the least amount. As with peas and carrots, injury to mint from a combination of the gases occurred at lower concentrations than were required to produce injury from either gas alone.

Beans

Exposures of the Tenderette cultivar of beans to SO_2 at a concentration of 2.75 ppm for 1 h produced injury symptoms. The SO_2 injury consisted of large discrete tan-necrotic areas on the upper leaf surface which is concentrated toward the margins.

Relative sensitivity of bean cultivars to O_3 and characteristic injury symptoms were determined by exposing 20 bean cultivars to 1.47 ppm O_3 for 1 h (Table 48). Several different types of O_3 injury symptoms were observed on particular cultivars (Butler 1978). One of these symptoms was necrotic flecking dispersed over most of the leaf area; individual lesions were small and increased in number with increasing severity of injury. Another type of symptom observed was a necrotic patching restricted to certain areas of the leaf; individual lesions were quite large and increased in size and number with increasing severity of injury. Small brown or purplish-brown pigmented lesions also were observed on some cultivars, and a generalized chlorosis also developed on a few plants of every cultivar. All these symptoms were restricted to the interveinal areas of the leaves; they were most apparent on the upper-leaf surfaces but also penetrated to the lower surfaces.

The types of symptoms developing on the different cultivars may be determined--in part--by the particular environmental conditions under which the beans were grown, and different O_3-symptom expressions of beans under different environmental conditions have been reported (Hill et al. 1970); differences in symptoms were not associated with relative sensitivity to O_3.

Additional studies were conducted in which two sensitive and two resistant bean cultivars from the screening study were exposed to O_3 for 1-, 2-, and 8-h periods with different O_3 concentrations (Table 49). Relative sensitivity of the cultivars was the same for the different exposure times. The relative sensitivity of different cultivars was similar between the short-duration, high-level exposures and the longer-duration, low-level exposures. Thus the more easily-conducted exposures of short duration appear to be acceptable for evaluating response of different cultivars of beans to O_3.

TABLE 48. RELATIVE SENSITIVITY OF BEAN CULTIVARS TO O_3*

Cultivar	Chlorophyll reduction (%)	Visual injury (%)
Sanilac	75.8 a†	81.9 a†
Tenderette	66.6 ab	69.3 ab
Blue Lake Stringless	64.1 abc	68.3 ab
Bush Blue Lake 290	63.2 abc	69.1 ab
Spurt	60.5 abcd	63.2 abcd
Apollo	53.8 abcde	67.2 abc
Early Gallatin	56.5 abcdef	59.3 bcde
Pinto	(56.3)	(59.8)
Bush Blue Lake 274	55.0 abcdef	65.8 abc
Bush Blue Lake 53	53.8 abcdef	51.6 cde
Cascade	51.6 bcdef	44.3 ef
Coloma	47.4 cdefg	24.2 g
Provider	45.5 defg	45.7 ef
Tendergreen	41.3 efg	33.5 fg
Orbit	41.2 efg	57.7 bcde
Resistant Asgrow Valentine	39.9 fg	49.2 de
Tempo	32.1 gh	31.6 fg
Black Turtle Soup	14.1 hi	20.5 g
French's Horticultural	13.9 i	19.9 g

*Bean plants were exposed to 1.47 ± 0.10 ppm O_3 for 1 h. Eight plants of each cultivar were used except for Sanilac and Black Turtle Soup for which four plants each were used.

†Means in a column followed by the same letter or letters are not significantly different at the 5% level by Duncan's Multiple Range test. Two Pinto plants were included in each exposure of a test cultivar; therefore statistical comparisons did not include Pinto.

TABLE 49. RELATIVE SENSITIVITY OF FOUR BEAN CULTIVARS TO O_3 AT DIFFERENT DOSAGES

Cultivar	O_3 dosage* 1 h at 1.37 ppm†	 2 h at 0.64 ppm†	 8 h at 0.25 ppm†
PERCENT CHLOROPHYLL REDUCTION			
Spurt	64.8 a‡	49.9 a	16.6 a
Blue Lake Stringless	51.6 b	24.7 b	5.6 b
Black Turtle Soup	19.7 c	17.9 bc	4.9 b
French's Horticultural	18.6 c	14.1 c	0.2 b
PERCENT VISUAL INJURY			
Spurt	76.8 a*	58.3 a	17.5 a
Blue Lake Stringless	63.9 a	18.6 b	9.4 b
Black Turtle Soup	14.4 b	2.3 c	0.0 c
French's Horticultural	17.5 b	4.7 c	0.0 c

*1-h exposures, n = 9; 2-h exposures, n = 6; 8-h exposures, n = 4.

†1 ppm O_3 ≃ 2,000 μg/m^3.

‡Means in a column followed by the same letter are not significantly different at the 5% level by Duncan's Multiple Range Test.

The sensitive cultivar Tenderette was selected for studies to determine the minimum threshold levels of pollutants for visible injury (Table 50). Very high levels of SO_2 were required to cause injury to Tenderette bean plants under laboratory conditions. Some injury was noted on plants exposed to 2.75 ppm for 1 h, but significant injury was found only at a concentration of 3.50 ppm for 1 h. Some injury with O_3 was observed at 0.40 ppm for 1 h, the highest level of O_3 tested. Combinations of O_3 and SO_2 were only evaluated at levels that did not greatly exceed maximum combination levels that might be found in the generating station area (0.08 ppm SO_2 and 0.08 ppm O_3 and 0.20 ppm SO_2 and 0.08 ppm O_3). No injury symptoms were seen with the combinations.

Alfalfa

Alfalfa is known to be sensitive to air pollutants and is grown extensively in the area of the generating station. Exposure of plants to SO_2 or O_3 produced somewhat similar symptoms. Both pollutants caused necrosis along leaf margins, especially near the tips. The damage from O_3, however, extended a little further into the leaf lamina from the margin than damage induced by SO_2. Sulfur dioxide sometimes caused a chlorotic mottling and at low concentrations caused pinpoint flecking along the veins that was not seen with O_3 exposures. With SO_2, the first fully developed trifoliate leaf at the base of the stem was less injured than were the second and third leaves, but with O_3 all three leaves were injured equally. The younger developing leaves showed little or no injury.

Results of exposure of five cultivars grown in Wisconsin to 1.35 ppm SO_2 for 4 h are indicated in Table 51. No significant difference at the 5% level in the percentage of chlorophyll reduction or visible leaf area injured was found among cultivars. Injury to Vernal alfalfa plants was quite variable, and this cultivar had a percentage of individual plants that were consistently more sensitive than plants of any other cultivar.

Plants of Vernal alfalfa were treated with SO_2 at different concentrations for 4 h to find the threshold for injury (Table 52). The minimum amount needed for appearance of injury was 0.70 ppm. Injury generally increased with increasing concentrations of SO_2, with about 25% injury at 1.0 ppm. When Vernal alfalfa was exposed to different O_3 concentrations the threshold of injury was found to be between 0.20 and 0.25 ppm for 4-h exposures (Table 52).

Vernal alfalfa plants also were exposed to combinations of SO_2 and O_3 (Table 52). An O_3 level of 0.13 ppm was used in combination with SO_2 at 0.26, 0.36, 0.51 and 0.69 ppm in 4-h exposures. As with other plants, alfalfa leaves were injured by lower concentrations of SO_2 and O_3 in combination than when exposed to the gases separately. The minimum combination injury levels are <0.13 ppm O_3 and 0.26 ppm SO_2 (Table 52).

TABLE 50. RESPONSE OF TENDERETTE BEAN EXPOSED TO SO_2, O_3, AND SO_2 PLUS O_3[*]

Pollutant			
SO_2 (ppm)[†]	O_6 (ppm)[†]	Visible injury (%)	Chlorophyll reduction (%)
1.75		0.0a[ξ]	2.6a
2.75		6.8b	6.2b
3.50		42.1c	32.1c
	0.10[‡]	0.0a	-5.6a
	0.20	0.0a	3.8b
	0.40	7.7b	18.5c
0.08	0.08	0.0a	1.6a
0.08	0.08	0.0a	-2.5a
0.20	0.08	0.0a	-3.2a
0.20	0.08	0.0a	0.6a

[*] Six treated and six control plants were used for each trial.

[†] 1 ppm $SO_2 \simeq 2{,}600\ \mu g/m^3$; 1 ppm $O_3 \simeq 2{,}000\ \mu g/m^3$.

[‡] Exposures with a single pollutant were for 1 h and with combined exposures for 4 h.

[ξ] Means in a column followed by the same letter are not significantly different at the 5% level by Duncan's Multiple Range Test.

TABLE 51. SENSITIVITY OF ALFALFA CULTIVARS TO SO_2*

Cultivar	Chlorophyll reduction† (%)	Leaf area injured† (%)
Agate	17.4	6
Apollo	18.3	12
Iroquois	19.1	10
Saranac	19.1	12
Vernal	15.6	33

*Plants were exposed to 1.35 ppm SO_2 (3,400 μg/m^3) for 4 h.

†Percentage of chlorophyll reduction and leaf area injured for six treated and six control plants. No significant difference in reduction between cultivars was found at the 5% level of significance as indicated by Duncan's New Multiple Range Test. Data are for the first three leaves.

TABLE 52. DOSAGE RESPONSE OF VERNAL ALFALFA EXPOSED TO SO_2, O_3, AND SO_2 PLUS O_3*

Pollutant		Chlorophyll reduction (%)	Leaf area injured (%)
SO_2 (ppm)†	O_3 (ppm)†		
0.70		9.3 a	1 a
0.80		12.2 a	5 a
1.00		24.3 a	26 b
1.35		28.8 a	33 b
	0.13	1.0 m	3 m
	0.20	3.6 m	4 m
	0.25	52.5 n	47 n
	0.30	48.8 n	53 n
	0.36	81.2 o	76 o
0.26	0.13	20.0 s	20 s
0.36	0.13	23.0 s	17 s
0.51	0.13	15.0 s	16 s
0.69	0.13	24.0 s	30 t

*All exposures for 4 h. Injury estimates in a column followed by different letters are significantly different at the 5% level as indicated by Duncan's New Multiple Range Test. Data are for the first three leaves above unifoliate leaf. Eight to 10 treated and control plants for each value.

†1 ppm SO_2 ≃ 2,600 μg/m^3; 1 ppm O_3 ≃ 2,000 μg/m^3.

SUMMARY

Considerable difference in pollution sensitivity exists among the crop species tested and among cultivars of most crops. Cultivars of alfalfa and peas were more sensitive to SO_2 and O_3 than were cultivars of other plants. The threshold sensitivity levels for sensitive cultivars--alfalfa and peas--were above the maximum recorded levels for these pollutants around the Columbia station. Therefore, no injury from the pollutants is anticipated.

Because the combination of SO_2 and O_3 caused injury to all crops at levels lower than each pollutant alone, the combination concentrations are of the greatest concern for plant injury. The probability is low, however, that elevated levels of both pollutants would occur at a time when the plants were highly sensitive to injury. This is because high sensitivity could occur only with favorable growing conditions and be limited to daylight hours when the stomates would be induced to open.

The percentage of leaf injury reported for the different crop species in this section is for the sensitive 1-3 leaves on the plants. Thus, the percentage of injury to all leaves on the plant would be considerably less. Also, leaf injury can not be utilized to project reductions in harvestable yield with any accuracy. No yield data was obtained for any of the crop species studies.

It should be stressed that the pollutant concentrations established as the minimum threshold levels for injury under controlled-exposure conditions do not provide exact values for determining the possibility and extent of injury under field conditions. One reason for this condition is that exposure conditions--particularly wind velocity over plants in the field--differ significantly from conditions in controlled-environment chambers. Compared with plants in controlled conditions, plants in the field at times absorb significantly more pollutant and have greater injury and at other times absorb significantly less pollutant and have less injury. Secondly, pollutant sensitivities of plants under field conditions are likely to differ from those under controlled-environment conditions because of differences in temperature, light, humidity, soil moisture, and pollutant exposure in the field environment.

Despite these differences between plants in the field and in the laboratory, the information from controlled studies is useful since it identifies those cultivars and species that are most resistant to injury and that should be recommended for planting if concentrations of pollutants are close to minimum-threshold levels. Such studies also provide data for worst-case situations and help provide needed baseline information to determine whether or not additional pollutant control procedures are needed.

SECTION 9

CONTROLLED EXPOSURES OF TREMBLING ASPEN TO AIR POLLUTANTS

To determine the nature of symptom development and minimum threshold injury levels in trembling aspen (*Populus tremuloides* Mich.), clonally-propagated trembling aspen plants were exposed to sulfur dioxide (SO_2) and ozone (O_3), singly and in combination. Root cuttings were taken from aspen stands in the vicinity of the Columbia Generating Station. Plants from several aspen clones were exposed to pollutants in order to determine relative sensitivity of the genetic variants to SO_2 and O_3. In the past, a limited number of controlled exposures of trembling aspen to air pollutants have been conducted (Treshow and Stewart 1973). Populus species and hybrids are known from field observations in polluted areas to be among the deciduous trees most sensitive to SO_2 (Linzon 1965).

PROCEDURES

Culture Methods

Root cuttings from 14 aspen trees were collected on 14 August 1973 from stands within 13 km of the power plant and were placed in moist sphagnum peat. Root sprouts were potted in 1 part sphagnum peat and 3 parts Plainfield sand with 7.8 g KNO_3, 5.2 g K_2SO_4, 52.3 g single superphosphate, 93.9 g dolomite lime, 26.1 g $CaCO_3$, and 26.1 g gypsum added for each 35 liters of soil mixture. A solution containing 10 ml of Hyponex fertilizer for each 4 liters of water was added on a weekly basis to the potted cuttings, which were grown in greenhouses with supplemental incandescent light for a 16-h photoperiod. Greenhouse temperature was maintained above 18°C during the day and 15°C at night. At least 250 plants of each of 10 aspen clones numbered 1, 2b, 2c, 3, 4, 5, 6b, 6c, 8, and 10 were used for the symptom expression and minimum threshold dose studies. Ten plants from each of the five aspen clones numbered 1, 6b, 6c, 8, and 10 were used for the genetic variation study.

Plants were exposed to pollutants at three development stages, which were identified as stage 1 for least mature, stage 2 for intermediate, and stage 3 for the most mature stage used. Plants at stage 1 were 10 cm in height and had an average of eight leaves all of juvenile form (lanceolate) not fully elongated. Plants at stage 2 averaged 25 cm in height and had an average of 15 leaves both juvenile and mature in form (suborbicular to broadly ovate). Plants at stage 3 averaged 45 cm in height and had an average of 22 leaves, all of mature form. The lowest juvenile leaves had abscised at stage 3.

Exposure Procedure

Three polyethylene-covered chambers (1.22 x 1.22 x 4.00 m); maintained in a greenhouse as decribed by Houston and Stairs (1973), were used. All chambers functioned as negative-pressure, single-pass systems with ambient air entering the chambers through activated charcoal-filters. Two chambers were used for maintaining plants free from exposure to ambient pollutants and one was used for fumigations. Fumigants were introduced between the intake filter and the plant material, drawn through the test plants, and then exhausted through aluminum ducts and a double charcoal-filter at the opposite end of the chamber. Sulfur dioxide from a pressurized cylinder served as the source of the SO_2. The SO_2 flow rate was metered by dual regulators (Matheson Gas Products Model Numbers 13-660 and 71AS) and a microneedle valve (Matheson Gas Products Model Number 1335G4). The SO_2 concentration was monitored by a Scientific Industries Model 60 SO_2 Analyzer which was calibrated at weekly intervals using SO_2 permeation tubes in an Analytical Instrument Development, Inc., Model 303 Gas Mixing Oven. Ozone was supplied by General Electric 64511 germicidal lamps; O_3 concentrations were monitored with a Mast O_3 Meter, Model 724-2, equipped with a CrO_3 scrubber to eliminate SO_2 interference and calibrated at monthly intervals with a Monitor Laboratories, Inc., Model 8501 O_3 Generator.

Injury-Scoring Procedure

Injury was estimated by two methods: 1. the percentage of total plants injured; 2. the average percentage of leaves injured per plant. The percentage of leaves injured per plant was scored 48 h after exposure to pollutants. Only leaves > 1 cm long were scored. Observations of symptom development were made twice daily for the first week and then daily for 1 month after exposures.

Plant Exposures

Stage of Development--

Plants at the three stages of development were exposed to 0.80 ppm SO_2* or 0.15 ppm O_3. Three ramets (individuals) of five clones at each development stage were exposed. The results were subjected to analysis of variance to determine statistical significance.

Symptom Expression and Minimum Threshold Injury Levels--

Ten plants from each of the aspen clones numbered 1, 2, 4, 5, 6, 6b, 6c, 8, 9, and 10 were exposed to SO_2 and O_3 at the following concentrations for 3 h: SO_2 at 0.20, 0.30, 0.50, and 0.65 ppm; O_3 at 0.05, 0.10, 0.15, and 0.20 ppm; SO_2 at 0.20 ppm plus O_3 at 0.05 ppm; and SO_2 at 1.35 ppm plus O_3 at 0.05 ppm. Symptom development was observed twice daily for the first week and then daily for 1 month after fumigations.

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*All pollutant concentrations in this section are reported in ppm taken directly from readings on the analyzer. The appropriate concentration for SO_2 is 1 ppm = 2,600 $\mu g/m^3$ and for O_3 is 1 ppm = 2,000 $\mu g/m^3$.

Genetic Variation--

Ten individuals of the aspen clones numbered 1, 6b, 6c, 8, and 10 were exposed to 0.50 ppm SO_2, 0.10 ppm O_3, and 0.35 ppm SO_2 plus 0.05 ppm O_3 for 3 h to determine between-clone variation in aspen sensitivity.

RESULTS AND DISCUSSION

Stage of Development

Results of exposure of five aspen clones to SO_2 and O_3 showed significant differences in sensitivity of clones at different developmental stages (Table 53 for complete ANOVA results). Since the stage of development was found to affect pollutant sensitivity of plants, only plants of development stage 3 were used for studies of threshold injury levels and genetic evaluation of sensitivity.

Leaf age appeared to be important in determining whether a given leaf was injured by SO_2 and O_3 exposures. Generally, the youngest leaves, i.e., those actively enlarging, were least injured by SO_2 or O_3. Recently mature (fully expanded) to old leaves (not yet beginning to yellow) were the most sensitive to SO_2. In contrast, the peak of O_3 sensitivity was observed only on recently mature leaves.

Threshold-Injury Levels

Minimum threshold-injury levels for trembling aspen were found to be lower than for the sensitive crop plants tested. Minimum-injury concentrations for the more sensitive aspen plants were 0.35 ppm SO_2 for 3 h, 0.05 ppm O_3 for 3 h and 0.20 ppm SO_2 plus 0.05 ppm O_3 for 3 h (Table 54, Table 55). Threshold concentrations varied considerably from clone to clone. For example, the threshold level for SO_2 injury varied from 0.35 ppm for clones 1, 6b, and 6c to 0.65 ppm for clones 8 and 10. Similarly, while the O_3-threshold concentrations were $\leq$ 0.05 ppm for clones 6b and 6c, 0.20 ppm O_3 was necessary to injure clone 8 (Table 54).

The importance of environmental variation in altering sensitivity of the clones is shown among the variation of sensitivity to a given level of SO_2 or O_3 among the ramets of each clone. At the threshold concentrations, for example, frequently < 50% of the 10 ramets of a clone would be injured. This within-clone variation might be expected if there were: position effects in the fumigation chambers, differences in ramets' growth rates, or differences in soil fertility or available water. The random nature of the injury occurrence in the chamber and the lack of any detected pollutant-concentration gradient in the chamber suggest that there were no obvious chamber position effects. Small differences in growth rates and/or

TABLE 53. ANALYSIS OF VARIANCE FOR FIVE TREMBLING ASPEN CLONES AT THREE DEVELOPMENT STAGES EXPOSED TO SO_2 AND O_3

Source	df	ss	ms	F
		EXPOSURE TO 0.80 PPM† SO_2 FOR 3 H		
Clones	4	3,085.5	771.3	4.93*
Ontogenetic stage	2	1,241.0	620.5	3.97**
Clones x stage	8	2,167.3	270.9	$1.73^{n.s.}$
Error	30	4,693.3	156.4	
Total	44			
		EXPOSURE TO 0.15 PPM O_3† FOR 3 H		
Clones	4	9,951.6	2,487.9	114.0*
Ontogenetic stage	2	701.0	350.5	$1.6^{n.s.}$
Clones x stage	8	9,678.4	1,209.8	5.53*
Error	30	5,453.3	218.8	
Total	44			

*Significant at $p < 0.01$

**Significant at $p < 0.05$.

†1 ppm SO_2 o 2,600 μg/m^3; 1 ppm O_3 o 2,000 μg/m^3.

TABLE 54. CONCENTRATION RESPONSE OF FIVE TREMBLING ASPEN CLONES EXPOSED TO SO_2, O_3, and SO_2 PLUS O_3

	Exposure to,					
	SO_2		O_3		$SO_2 + O_3$	
Clone	Plants injured	Leaves injured (%)*	Plants injured	Leaves injured (%)*	Plants injured	Leaves injured (%)*
	0.20 ppm†		0.05 ppm†		(0.20 + 0.05 ppm)†	
1	0	0	0	0	6	11
6b	0	0	3	3.6	2	1.6
6c	0	0	3	3.5	8	18
8	0	0	0	0	0	0
10	0	0	0	0	2	1.2
Total	0		6		18	
	0.35 ppm		0.10 ppm		(0.035 + 0.05 ppm)	
1	4	3.4	0	0	6	16
6b	5	4.4	1	0.70	9	20
6c	1	2.0	3	4.3	9	8.9
8	0	0	0	0	0	0
10	0	0	1	0.65	1	0.7
Total	10		5		25	
	0.50 ppm		0.15 ppm			
1	10	46	3	4.2		
6b	4	10	3	7.2		
6c	2	1.2	5	6.5		
8	0	0	0	0		
10	0	0	1	0.75		
Total	16		12			
	0.65 ppm		0.20 ppm			
1	10	45	10	37		
6b	9	22	10	34		
6c	10	21	8	32		
8	5	13	4	5.9		
10	6	11	5	25		
Total	40		38			

*Ten plants/clone were exposed at each concentration for 3 h.

†1 ppm $SO_2 \simeq 2{,}600\ \mu g/m^3$; 1 ppm $O_3 \simeq 2{,}000\ \mu g/m^3$.

differences in soil fertility and water use probably accounted for the within-clone variability in injury from the pollutants.

TABLE 55. MINIMUM THRESHOLD-INJURY CONCENTRATIONS FOR TREMBLING ASPEN EXPOSED TO POLLUTANTS

	SO_2	O_6	SO_2 plus O_3
Concentration*	0.35 ppm (3 h)	0.05 ppm (3 h)	0.20 ppm + 0.05 ppm (3 h)

*1 ppm $SO_2 \simeq$ 2,600 $\mu g/m^3$; 1 ppm $O_3 \simeq$ 2,600 $\mu g/m^3$.

Injury Symptom Development

Table 56 summarizes injury-symptom description and development rate for trembling aspen plants exposed to the pollutants. With SO_2, bifacial marginal and interveinal chlorosis and necrosis--characteristic of acute SO_2 injury on broad-leaved trees (Dochinger and Seliskar 1970)--were the most commonly found symptoms. The timing of symptom development was dependent on SO_2 concentrations. With low SO_2 concentrations (0.35 ppm), symptoms generally developed from 20 to 48 h after exposure. With high SO_2 concentrations (> 0.65 ppm), however, symptom development started within a few hours after initiation of exposure and continued to intensify until about 48 h after exposure. Severely injured leaves often senesced prematurely.

The most common O_3 injury symptoms were bifacial interveinal and marginal chlorosis and necrosis similar to symptoms from SO_2. Stippling or mottling of the upper leaf surface--the most commonly reported symptoms of O_3 injury to deciduous trees (Dochinger and Seliskar 1970)--did not occur. The timing of symptom development depended on pollutant concentration. After exposure to low O_3 concentrations, (< 0.05 ppm), symptoms generally appeared 20 to 48 h after exposure. In contrast, symptoms developed before 20 h following exposure to high O_3 concentrations (> 0.20 ppm).

Because primary symptoms of SO_2 and O_3 injury were similar, other symptoms were found to be more useful in differentiating between SO_2- and O_3- induced injury. Following severe SO_2 doses, leaves often had a water-soaked appearance and/or underwent guttation, wilting, drooping, and bleaching. None of these symptoms were observed after O_3 exposure. Another distinguishing characteristic is that the SO_2- induced injury almost always remained interveinal, while high O_3- induced injury often extended across the veins. Symptom expression after 48 h was useful in distinguishing between SO_2- and O_3-induced injury. For SO_2 injury, necrotic areas were dark brown to black after 48 h, and began to fade rapidly to light tan or

TABLE 56. CHARACTERISTIC INJURY SYMPTOMS ON TREMBLING ASPEN LEAVES FOLLOWING EXPOSURE TO SO_2, O_3, AND SO_2 PLUS O_3

Pollutant	Time (h)	Symptoms following 3-h exposure:	
		Low concentration	High concentration
		0.35 ppm*	0.65 ppm
SO_2	0-20	None	Bifacial, marginal, and interveinal chlorosis which rapidly becomes necrotic; water-soaked appearance, drooping, curling, bleaching, guttation, wilting.
	20-48	Bifacial, marginal, and interveinal chlorosis which gradually becomes necrotic (gray to black).	Increase in size of necrotic areas; gray to black color begins to fade to reddish brown.
	48+	Gray to black color fades rapidly to reddish brown and then to light tan or ivory.	Reddish brown color fades rapidly to light tan or ivory; premature drop of severely injured leaves.
		0.05 ppm*	0.20 ppm
O_3	0-20	Purple pigmentation on upper leaf surface (only on one clone).	Bifacial, marginal, and interveinal chlorosis which rapidly becomes necrotic (dark black); curling.
	20-48	Bifacial, marginal, and interveinal chlorosis which gradually becomes necrotic (dark black).	Increase in size of necrotic areas and necrosis, extends across veins.

Continued

Table 56 (cont.)

Pollutant	Time (h)	Symptoms following 3-h exposure: Low concentration	Symptoms following 3-h exposure: High concentration
	48+	Black color fades slowly to light tan or gray.	Black color fades slowly to light tan or gray; premature drop of severely injured leaves.
		(0.25 ppm SO_2 + 0.05 ppm O_3)	(1.40 ppm SO_2 + 0.15 ppm O_3)
$SO_2 + O_3$	0-20	None	Bifacial, marginal, and interveinal chlorosis which rapidly becomes necrotic; curling, bleaching.
	20-48	Bifacial, marginal, and interveinal chlorosis which gradually becomes necrotic.	Necrotic areas enlarge and show distinctly different color zones (with black and reddish brown predominating).
	48+	Necrotic areas begin to show different color zones (with black and reddish brown predominating); differential fading of necrotic areas to gray and tan.	Differential fading of necrotic areas to gray and tan; premature leaf drop.

*1 ppm $SO_2 \simeq$ 2,600 μg/m^3; 1 ppm $O_3 \simeq$ 2,000 μg/m^3.

ivory color. This color persisted until leaf drop. In contrast, O_3-induced black necrosis remained very dark for 7 to 10 days, gradually faded to gray-black or tan. This color again persisted until leaf drop.

Symptom development following exposure with combinations of SO_2 and O_3 was similar to that observed for each pollutant applied singly. The one exception to this pattern was that necrotic areas were not limited to one basic color as they were with injury caused by SO_2 or O_3 alone. In contrast, sections of necrotic areas frequently had two distinct colors, generally reddish brown and black. This color differentiation remained until leaf drop.

Genetic Variation

Table 57 summarizes relative sensitivities of the 10 aspen clones to SO_2, O_3, singly and in combination. As can be seen, the clones tested that were sensitive to SO_2 were also sensitive to O_3 and to SO_2 plus O_3, and the clones varied widely in sensitivity. Precise injury levels for some clones are given in Table 54.

TABLE 57. RELATIVE SENSITIVITY OF 10 TREMBLING ASPEN CLONES TO SO_2, O_3, AND SO_2 PLUS O_3

	Clone		
Pollutant	Sensitive	Intermediate	Tolerant
SO_2	1,6b,6c	2b,2c,4,10	3,5,8
O_3	1,6b,6c	2b,2c,5,8	3,4,10
$SO_2 + O_3$	1,6b,6c	2c,3,4,6*	2b,8,10

*Because of a disease problem, clone 6 was substituted for clone 5 in the $SO_2 + O_3$ fumigations.

SUMMARY

The sensitivity of different clones varied widely. Since the minimum threshold-injury levels for SO_2 were greater than any levels of SO_2 monitored around the station, no injury from SO_2 alone is anticipated. On the other hand, since the minimum threshold-injury levels of O_3 were less than the common background levels of O_3 in the area, pollutant injury would be possible from the background levels of O_3. The combination of background O_3 concentrations plus SO_2 concentrations from the station is potentially of greatest concern because injury occurred at lower concentrations of the pollutants when combined. The infrequent occurrence of elevated levels of both pollutants, however, reduces the possibility of injury.

REFERENCES

Ahmadjian, V., and M. E. Hale. The Lichens. Academic Press, New York, 1973. 697 pp.

Applied Science Associates. Diagnosing Vegetation Injury Caused by Air Pollution. EPA-450/3-78-005, U.S. Government Printing Office, Washington, D.C., 1978. 160 pp.

Beals, E. Forest Bird Communities in the Apostle Islands of Wisconsin. Wilson Bull., 72:156-181, 1960.

Bennett, J. P., and R. J. Oshima. Carrot Injury and Yield Response to Ozone. J. Amer. Soc. Hort. Sci., 101(6):638-639, 1976.

Berry, C. R. The Differential Sensitivity of Eastern White Pine to Three Types of Air Pollution. Can. J. Forest Res., 3:543-547, 1973.

Bray, J. R., and J. T. Curtis. An Ordination of the Upland Forest Communities of Southern Wisconsin. Ecological Monographs, 27:325-349, 1957.

Butler, L. L. Mechanisms and Inheritance of Resistance to Ozone in *Phaseolus vulgaris* L. Ph.D. Dissertation, University of Wisconsin, Madison, 1978. 75 pp.

Chapman, M. U. Diagnostic Criteria for Plants and Soils. University of California Division of Agricultural Survey, Riverside, California, 1966.

Costonis, D. C. Acute Foliar Injury of Eastern White Pine Induced by Sulfur Dioxide and Ozone. Phytopathology, 60:994-999, 1970.

Costonis, D. C. Injury to Eastern White Pine by Sulfur Dioxide and Ozone Alone and in Mixtures. European J. Forest Path., 3:50-55, 1973.

Costonis, D. C., and W. A. Sinclair. Relationship of Atmospheric Ozone to Needle Blight of Eastern White Pine. Phytopathology, 59:1566-1574, 1969.

Culberson, W. L. The Corticolous Communities of Lichens and Bryophytes in the Upland Forests of Northern Wisconsin. Ecological Monographs, 25:215-231, 1955a.

Culberson, W. L. Qualitative and Quantitative Studies on the Distribution of Corticolous Lichens and Bryophytes in Wisconsin. Lloydia, 18:25-36, 1955b.

Curtis, J. T. The Vegetation of Wisconsin. University of Wisconsin Press, Madison, Wisconsin, 1959. 657 pp.

Curtis, J. T., and R. P. McIntosh. An Upland Forest Continuum in the Prairie-Forest Border Region of Wisconsin. Ecology, 32:476-496, 1951.

Dochinger, L. S., E. W. Bender, F. L. Fox, and W. W. Heck. 1970. Chlorotic Dwarf of Eastern White Pine Caused by an Ozone and Sulphur Dioxide Interaction. Nature 225:476.

Dochinger, L. S., and C. E. Seliskar. Air Pollution and the Chlorotic Dwarf Disease of Eastern White Pine. Forest Sci., 16:46-55, 1970.

Dreisinger, B. R., and P. C. McGovern. Monitoring Atmospheric Sulfur Dioxide and Correlating Its Effects on Crops and Forest in the Sudbury Area. In: Impact of Air Pollution on Vegetation Conferences, S. W. Linzon, ed. Air Pollution Control Association, Pittsburgh, Pennsylvania, 1970. pp. 12-28.

Eversman, S. Effects of Low-Level SO_2 on *Usnea* and *Parmelia chlorochroa*. The Bryologist, 81(3):368-377, 1978.

Ferry, B. W., M. S. Baddeley, and D. L. Hawksworth, eds. Air Pollution and Lichens. University of Toronto Press, Toronto, Ontario, Canada, 1973.

Fink, B. The Lichen Flora of the United States. University of Michigan Press, Ann Arbor, Michigan, 1935. 426 pp.

Gordon, A. G., and E. Gorham. Ecological Aspects of Air Pollution for an Iron-Sintering Plant at Wawa, Ontario, Canada, Canada J. Bot., 41:1063-1078, 1963.

Gordon, C. C., P. C. Tourangeau, and P. M. Rice. Investigations of the Impact of Coal-Fired Power Plant Emissions upon the Disease/Health/Growth Characteristics of Ponderosa Pine-Skunkbush Ecosystems and Grassland Ecosystems in Southeastern Montana. In: The Bioenvironmental Impact of a Coal-Fired Power Plant Third Interim Report, Colstrip, Montana, EPA 1.23:600/3-78-021, E. M. Preston and R. A. Lewis, eds., U.S. Environmental Protection Agency, Corvallis Environmental Research Laboratories, Corvallis, Oregon, 1978.

Guderian, R. Air Pollution. Springer-Verlag. Berlin-Heidelberg-New York, 1977. 150 pp.

Guderian, R., and H. Schoenbeck. Recent Results for Recognition and Monitoring of Air Pollutants with the Aid of Plants. In: Proceedings of the Second International Clean Air Congress, H. M. England and W. T. Berry, eds., Academic Press, New York, 1971. pp. 266-273.

Hale, M. E. Phytosociology of Corticolous Cryptogams in the Upland Forests of Southern Wisconsin. Ecology, 36:45-63, 1955.

Hale, M. E. How to Know the Lichens. William C. Brown, Dubuque, Iowa, 1969. 226 pp.

Heagle, A. S., D. E. Body, and W. W. Heck. An Open-Top Field Chamber to Assess the Impact of Air Pollution on Plants. J. Environ. Qual., 1(3):365-368, 1973.

Heagle, A. S., R. B. Philbeck, H. H. Rogers, and M. B. Letchworth. Dispensing and Monitoring Ozone in Open-Top Field Chambers for Plant Effects Studies. Phytopathology, 69:15-20, 1979.

Heggestad, H. E., R. K. Howell, and J. H. Bennett. The Effects of Oxidant Air Pollutants on Soybeans, Snap Beans and Potatoes. Ecological Research Series EPA 600/3-77-128, NTIS, Springfield, Virginia, 1977. 38 pp.

Hepting, G. H. Diseases of Forest and Tree Crops Caused by Air Pollutants. Phytopathology, 58(8):1098-1101, 1968.

Hill, A. C., M. R. Pack, M. Treshow, and R. F. Downs. Plant Injury Induced by Ozone. Phytopathology, 51:356-363, 1961.

Hill, A. C., H. E. Heggestad, and S. N. Linzon. Ozone. In: Recognition of Air Pollution Injury to Vegetation: A Pictorial Atlas. J. S. Jacobson, and A. C. Hill, eds., Air Pollution Control Association, Pittsburg, Pennsylvania, 1970.

Hill, D. J. Some Effects of Sulphite on Photosynthesis in Lichens. New Phytologist., 73:1193-1205, 1974.

Hoeft, R. G., and L. M. Walsh. Effect of Carrier, Rate and Time of Application of S on the Yield, and S and N Content of Alfalfa. Agron. J., 67:427-430, 1975.

Hoeft, R. G., L. M. Walsh, and D. R. Keeney. Evaluation of Various Extractants for Available Soil Sulfur. Soil Sci. Soc. Amer. Proc., 37:401-404, 1973.

Houston, D. B. Physiological and Genetic Response of *Pinus strobus* L. Clones to Sulfur Dioxide and Ozone Exposures. Ph.D. Dissertation, University of Wisconsin, Madison, Wisconsin, 1970.

Houston, D. B. Response of Selected *Pinus strobus* L. Clones to Fumigations with Sulfur Dioxide and Ozone. Canada J. Forest. Res., 4:65-68, 1974.

Houston, D. B., and G. R. Stairs. 1973. Genetic Control of Sulfur Dioxide and Ozone Tolerance in Eastern White Pine. Forest Sci., 19:267-271, 1973.

Jacobson, J. S., and A. C. Hill. Recognition of Air Pollution Injury to Vegetation: A Pictorial Atlas. Air Pollution Control Association, Pittsburgh, Pennsylvania, 1970.

Jenkins, R., and J. L. Devries. Practical X-Ray Spectrometry. Springer-Verlag, New York, 1973.

Kats, G., C. R. Thompson, and W. C. Kuby. Improved Ventilation of Open Top Greenhouses. J. Air Pollution Control Assoc., 26:1089-1090, 1976.

Katz, M. Sulphur Dioxide in the Atmosphere and its Relation to Plant Life. Ind. Eng. Chem., 41(11), 2450-2465, 1949.

Knudson, L. L., T. W. Tibbitts, and G. E. Edwards. Measurement of Ozone Injury by Determination of Leaf Chlorophyll Concentration. Plant Physiol., 60:600-608, 1977.

LeBlanc, F., and D. N. Rao. Effects of Sulphur Dioxide on Lichen and Moss Transplants. Ecology, 53:612-617, 1973.

LeBlanc, F., and D. N. Rao. Effects of Air Pollutants on Lichens and Bryophytes. In: Response of Plants to Air Pollution, J. B. Mudd, and T. T. Kozlowski, eds., Academic Press, New York, N.Y., 1975. pp. 237-272.

Lee, J. J., E. M. Preston, and D. Weber. Temporal Variation in SO_2 Concentration on ZAPS. In: The Bioenvironmental Impact of a Coal-Fired Power Plant, Fourth Interim Report, EPA 600/3-79-004. Colstrip, Montana, E. M. Preston, and T. L. Gullett, eds., Corvallis Environmental Research Laboratories, U.S. Environmental Protection Agency, Corvallis, Oregon, 1979. pp. 284-305.

Linzon, S. N. Sulfur Dioxide Injury to Trees in the Vicinity of Petroleum Refineries. Forestry Chronicle, 41:245-247, 1965.

List, R. J. Smithsonian Meteorological Tables, Sixth Revised Edition. Smithsonian Miscellaneous Collections Vol. 114, Smithsonian Institute, Washington, D.C., 1968. 527 pp.

MacLean, D. C., and R. E. Schneider. Photochemical Oxidants in Yonkers, New York: Effects on Yield of Bean and Tomato. J. Environ. Qual., 2:371-376, 1976.

Mandl, R. H., L. H. Weinstein, D. C. McCune, and M. Keveny. A Cylindrical, Open-Top Chamber for the Exposure of Plants to Air Pollutants in the Field. J. Environ. Qual., 2:371-376, 1973.

Menzer, H. A., and H. E. Heggestad. Ozone and Sulfur Dioxide Synergism: Injury to Tobacco Plants. Science, 153:424-425, 1966.

Miller, P. R., and J. R. McBride. Effects of Air Pollutants on Forests. In: Responses of Plants to Air Pollution, J. B. Mudd, and T. T. Kozlowski, eds., Academic Press, New York, N.Y., 1975. pp. 195-235.

Munsell Color Company, Inc., ed. Munsell Book of Color. Pocket Edition, Baltimore, Maryland, 1942.

Musselman, R. C., W. J. Kender, and D. E. Crowe. Determining Air Pollutant Effects on the Growth and Productivity of "Concord" Grapevines Using Open-Top Chambers. J. Amer. Soc. Hort. Sci., 103(5):645-648, 1978.

Nash, T. H., III. Sensitivity of Lichens to Sulfur Dioxide. The Bryologist, 76:333-339, 1973.

Nash, T. H., III. Influence of Effluents from a Zinc Factory on Lichens. Ecological Monographs, 45(2):183-198, 1975.

Newberry, G. The Influence of a Sulfate-Process Paper Mill on Corticolous Lichens. The Bryologist, 77:561-576, 1974.

Nieboer, E., H. M. Ahmed, K. J. Puckett, and D. H. S. Richardson. Heavy Metal Content of Lichens in Relation to Distance from a Nickel Smelter in Sudbury, Ontario. Lichenologist, 5:292-304, 1972.

O'Hare, G. P., and P. Williams. Some Effects of Sulfur Dioxide Flow on Lichens. Lichenologist, 7:116-120, 1975.

Ormrod, D. P. Sensitivity of Pea Cultivars to Ozone. Plant Disease Reporter, 60(5):423-426, 1976.

Pollanschutz, J. Die Ertragskundlichen Messmethoden zur Erkennung und Peurteilungvon von Forslichen Rauchshaden. Mitt Forst. Bundesversuchsanst., Wein, 92:155-206, 1971.

Puckett, K. J., E. Nieboer, W. P. Flora, and D. H. S. Richardson. Sulphur Dioxide: Its Effect on Photosynthetic C^{14} Fixation in Lichens and Suggested Mechanisms of Phytotoxicity. New Phytologist, 72:141-154, 1973.

Ragland, K. W., B. D. Goodell, and T. L. Coughlin. Air Pollution Studies Near a Coal-Fired Power Plant. Wisconsin Power Plant Impact Study. EPA 600/3-80-048. U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980. 102 pp.

Reinert, R. A. Monitoring, Detecting, and Effects of Air Pollutants on Horticultural Crops: Sensitivity of Genera and Species. Hort. Science, 10:495-500, 1975.

Reinert, R. A., and T. N. Gray. Growth of Radish, Tomato, and Pepper Following Exposure to NO_2, SO_2, and O_3 Singly or in Combination. Hort. Science, 12(4):402, 1977.

Rohweder, D. A., E. H. Fisher, and E. W. Hanson. Alfalfa Analyst. Wisconsin Agr. Expt. Sta. Bull. A2417, Madison, Wisconsin, 1972.

Rominger, R. S., D. Smith, and L. A. Peterson. Yields and Elemental Composition of Alfalfa Plant Parts at Late Bud Under Two Fertility Levels. Canada J. Plant Sci., 55:69-75, 1975.

Runeckles, V.C., and P.M. Rosen. Effects of Pretreatment with Low Ozone Concentrations on Ozone Injury to Bean and Mint. Can. J. Bot. 52:2607-2610, 1974.

Seim, E. C., A. C. Caldwell, and G. W. Rehm. Sulfur Response by Alfalfa (*Medicago satina* L.) on a Sulfur Deficient Soil. Agron. J., 61:368-371, 1969.

Severs, R. K. Simultaneous Total Oxidant and Chemiluminescent Ozone Measurements in Ambient Air. J. Air Pollution Control Assoc., 25(4):394-396, 1975.

Showman, R. E. Lichens as Indicators of Air Quality Around a Coal-Fired Power Generating Plant. The Bryologist, 78:1-6, 1975.

Snedecor, G. W. and W. G. Cochran. Statistical Methods. Iowa State University Press, Ames, Iowa, 1967.

Sorenson, I. A Method of Establishing Groups of Equal Amplitude in Plant Sociology Based on Similarity of Species Content. Det. Kong. Danske Vidensk. Selsk. Biol. Skr., Copenhagen, Denmark, 5(4):1-34, 1948.

Steel, R. G. D., and J. H. Torrie. Principles and Procedures of Statistics. McGraw-Hill, New York, N.Y., 1960.

Stone, L. L., and J. M. Skelly. The Growth of Two Forest Tree Species Adjacent to a Periodic Source of Air Pollution. Phytopathology, 64:773-778, 1974.

Taylor, O. C. Testimony Before United States Congress House Committee on Science and Technology. Subcommittee on Environment and the Atmosphere. Costs and Effects of Chronic Exposure to Low Level Pollutants in the Environment. Hearing Nov. 7-17, 1975, Superintendent of Documents 84, Washington, D.C. pp. 454.

Tingey, D. T., R. A. Reinert, J. A. Dunning, and W. W. Heck. Vegetation Injury from the Interaction of Nitrogen Dioxide and Sulfur Dioxide. Phytopathology, 61:1506-1511, 1971.

Treshow, M., and D. Stewart. Ozone Sensitivity of Plants in Natural Communities. Biol. Conserv., 5:209-214, 1973.

Türk, R., V. Wirth, and O. L. Lange. CO_2-Gaswechsel-Untersuchungen zur SO_2 Resistenz von Flechten. Oecologia, 15:33-64 (English abstract), 1974.

United States Department of Health, Education and Welfare. Air Quality Criteria for Photochemical Oxidants. A. P. 63, National Air Pollution Control Association, Washington, D.C., 1970.

U.S. Environmental Protection Agency. Preconference Report: Official Air Pollution Abatement Activity, Mt. Storm, West Virginia-Gorman, Maryland. Publ. 1, APTD-0656, NTIS PB199-181, Air Pollution Control Office, Research Triangle Park, North Carolina, 1971.

U. S. Environmental Protection Agency. Effects of Sulfur Oxides in the Atmosphere on Vegetation. EPA-R3-73-030, National Environmental Research Center, Office of Research and Development, Research Triangle Park, North Carolina, 1973.

Will-Wolf, S. Lichens for Bioassay of SO_2 Emissions. Institute for Environmental Studies, Report 75, University of Wisconsin, Madison, Wisconsin, 1977.

Wukash, R. T., and G. Hofstra. Ozone and Botrytis spp. Interaction in Onion Leaf Dieback: Field Studies. J. Amer. Soc. Hort. Sci, 102(5):543-546, 1977.

APPENDIX A

MONTHLY AVERAGE SO_2 CONCENTRATIONS ($\mu g/m^3$) FOR MARCH 1973 THROUGH JUNE 1978 AT CONTINUOUS MONITORING SITES

Month	Site 2 Cemetery (7 km N)	Site 3 Lake George (6 km E)	Site 4 Dekorra (4 km SSW)	Site 5 Messer (7 km W)	Site 8 Genrich (8 km N)	Site 9 Bernander (14 km E)	Site 10 Russell (16 km NE)
				1973			
Mar.	7.3(744)*	6.4(744)		7.6(744)			
Apr.	3.2(720)	2.8(720)		2.7(720)			
May	8.7(744)	2.4(744)		2.8(744)			
June	6.8(720)	2.8(720)		1.6(720)			
July	3.1(744)	5.8(744)	11.2(744)	3.2(744)			
Aug.	2.4(744)	7.3(744)	3.2(744)	1.6(744)			
Sept.	6.8(720)	10.9(720)	10.1(720)	2.2(720)			
Oct.	3.9(744)	3.5(744)	4.4(744)	1.5(744)			
Nov.	5.6(720)	4.0(720)	3.4(720)	3.1(720)			
Dec.	9.0(744)	5.3(744)	4.4(744)	2.3(744)			
				1974			
Jan.	3.6(744)	6.0(744)	7.5(744)	8.2(744)			
Feb.	9.8(432)	3.5(504)	10.2(672)	4.3(600)			
Mar.	2.4(720)	2.0(624)	3.4(744)	1.8(744)			
Apr.	4.7(552)	3.4(672)	3.4(600)	2.5(552)			
May	4.6(396)	1.8(648)	2.3(360)	2.8(552)			
June	1.5(720)	1.2(576)	5.0(432)	1.0(720)			
July	1.5(696)	2.2(528)	1.2(408)	1.4(696)			
Aug.	1.2(744)	1.3(696)	1.0(144)	1.4(624)			
Sept.	1.3(480)	1.4(552)	3.5(360)	2.2(648)			
Oct.	5.1(744)	2.4(744)	4.4(744)	3.6(744)			
Nov.	6.8(720)	5.0(720)	5.9(456)	5.3(720)			
Dec.	8.5(744)	7.4(744)	10.0(384)	6.5(648)			
				1975			
Jan.	8.7(720)	10.3(624)	7.8(504)	10.0(744)			
Feb.	8.9(624)	7.8(672)	12.8(552)	4.2(672)			
Mar.	7.9(744)	5.2(480)	7.1(744)	2.2(720)			
Apr.	4.0(672)	5.2(552)	4.4(672)	2.1(456)			
May	2.4(672)	7.3(696)	8.7(600)	1.8(696)			
June	2.7(720)	6.6(720)	6.0(672)	2.0(720)			
July	1.5(696)	7.2(624)	6.9(720)	1.4(648)			
Aug.	4.5(720)	6.6(648)	2.3(720)	No data			
Sept.	5.2(528)	8.9(600)	No data	5.7(672)			
Oct.	8.0(744)	2.6(648)	13.4(240)	4.0(672)			
Nov.	3.2(636)	6.0(408)	7.1(552)	3.8(720)			
Dec.	5.0(696)	6.0(720)	6.2(696)	1.4(744)			

APPENDIX A (cont.)

Month	Site 2 Cemetery (7 km N)	Site 3 Lake George (6 km E)	Site 4 Dekorra (4 km SSW)	Site 5 Messer (7 km W)	Site 8 Genrich (8 km N)	Site 9 Bernander (14 km E)	Site 10 Russell (16 km NE)
				1976			
Jan.	14.4(720)	17.4(660)	11.9(600)	1.0(744)			
Feb.	6.4(528)	9.0(558)	4.7(624)	No data			
Mar.	8.0(717)	22.8(617)	14.4(656)	13.1(582)			
Apr.	11.0(112)	11.6(720)	17.9(652)	16.4(709)†			
May	8.0(116)	18.1(743)	23.6(732)	23.0(742)†	9.6(621)	10.8(571)	13.8(582)
June		14.3(500)	14.3(703)†	20.4(717)†	8.6(523)	8.7(699)	13.4(671)
July		14.7(327)	12.3(662)	18.7(730)	13.2(718)	8.3(736)†	11.3(728)
Aug.		9.1(632)	13.3(729)	11.5(739)	11.4(733)	7.8(727)	8.9(726)
Sept.		7.7(717)	12.7(717)	12.4(717)	11.0(714)	7.8(717)	9.0(714)
Oct.		10.4(744)	11.5(716)	10.0(744)	10.2(744)	7.7(744)	7.9(744)
Nov.		8.8(719)	9.0(720)	8.0(714)	7.7(714)	7.6(714)	8.2(715)
Dec.		13.4(727)	10.9(714)	13.8(723)	13.8(728)	12.2(724)	12.8(727)
				1977			
Jan.		20.8(744)*	16.1(744)	24.5(742)	16.9(744)	21.0(740)	16.9(727)
Feb.		11.6(672)‡	7.8(672)	9.2(672)	8.9(672)	12.0(672)	9.7(672)
Mar.		9.3(740)	9.0(729)	8.7(701)	10.0(735)	10.4(738)	9.1(741)
Apr.		10.7(696)	11.5(711)	9.5(701)	13.1(707)‡	9.6(647)	11.6(694)
May		9.8(744)	12.6(657)	11.0(744)	13.3(744)‡	9.5(692)	10.5(741)
June		12.7(698)	8.6(660)	8.2(678)	10.6(713)	9.2(708)	10.6(708)
July		13.7(330)	7.0(740)	8.2(737)	7.1(719)	12.8(744)	8.8(744)
Aug.		7.7(712)	6.6(744)	7.4(695)	10.9(744)	18.3(741)	7.1(732)
Sept.		6.1(665)	7.5(716)	8.4(609)	7.7(708)	8.5(545)	7.7(713)
Oct.		7.8(673)	7.3(730)	8.2(733)	7.5(733)§	9.1(702)	12.0(730)
Nov.		15.9(679)	11.7(527)	22.3(519)	7.5(520)	9.4(703)	14.1(590)
Dec.		13.8(713)	14.8(692)	23.1(692)	11.8(685)	12.5(422)	15.7(714)
				1978			
Jan.		15.7(740)*	11.1(744)	19.4(733)	19.2(719)	15.4(695)	17.0(716)
Feb.		12.7(650)	9.3(646)	15.0(644)	13.8(637)	14.4(646)	12.2(600)
Mar.		7.4(626)	10.1(712)	10.9(706)	10.2(631)	10.5(712)	10.8(710)
Apr.		7.9(703)	12.2(687)	9.8(679)	7.4(605)	7.1(693)	8.0(672)
May		11.4(705)	9.6(667)	9.9(710)	8.6(695)	6.9(713)	11.4(698)
June		7.6(697)	7.3(572)	9.4(690)	13.3(692)	8.1(662)	6.8(690)

*Number in parentheses are hours of valid data for each month.

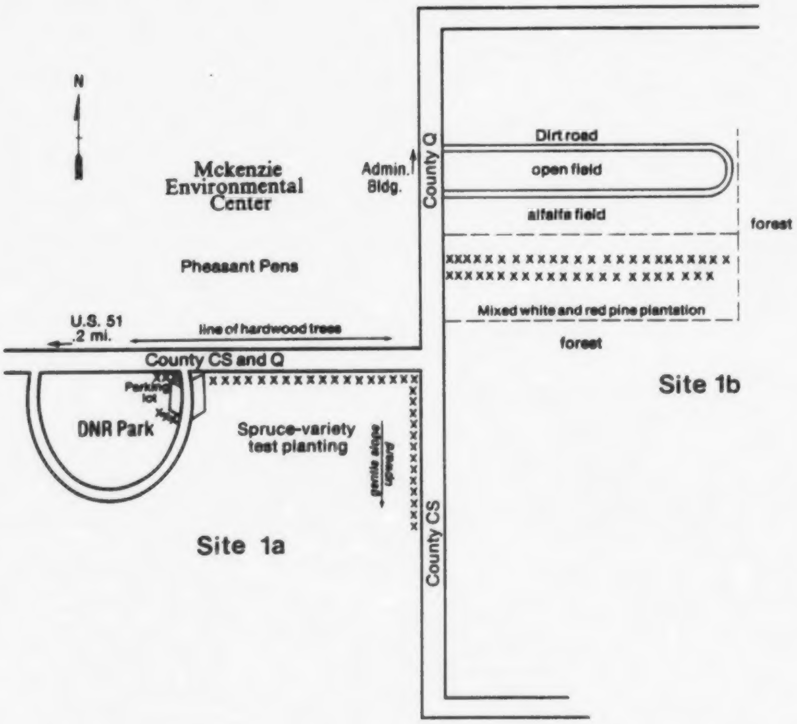
†Concentrations are increased because of inaccurate calibrations.

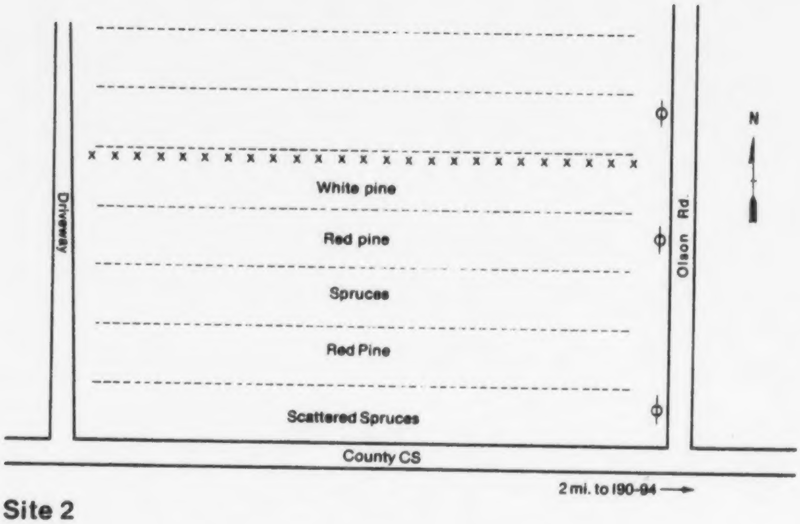
‡Concentrations are increased significantly because of inaccurate analyzer calibration during these months.

§Concentrations are lower than other sites because analyzer was inoperable during extended period of high background levels that were recorded at other sites.

APPENDIX B

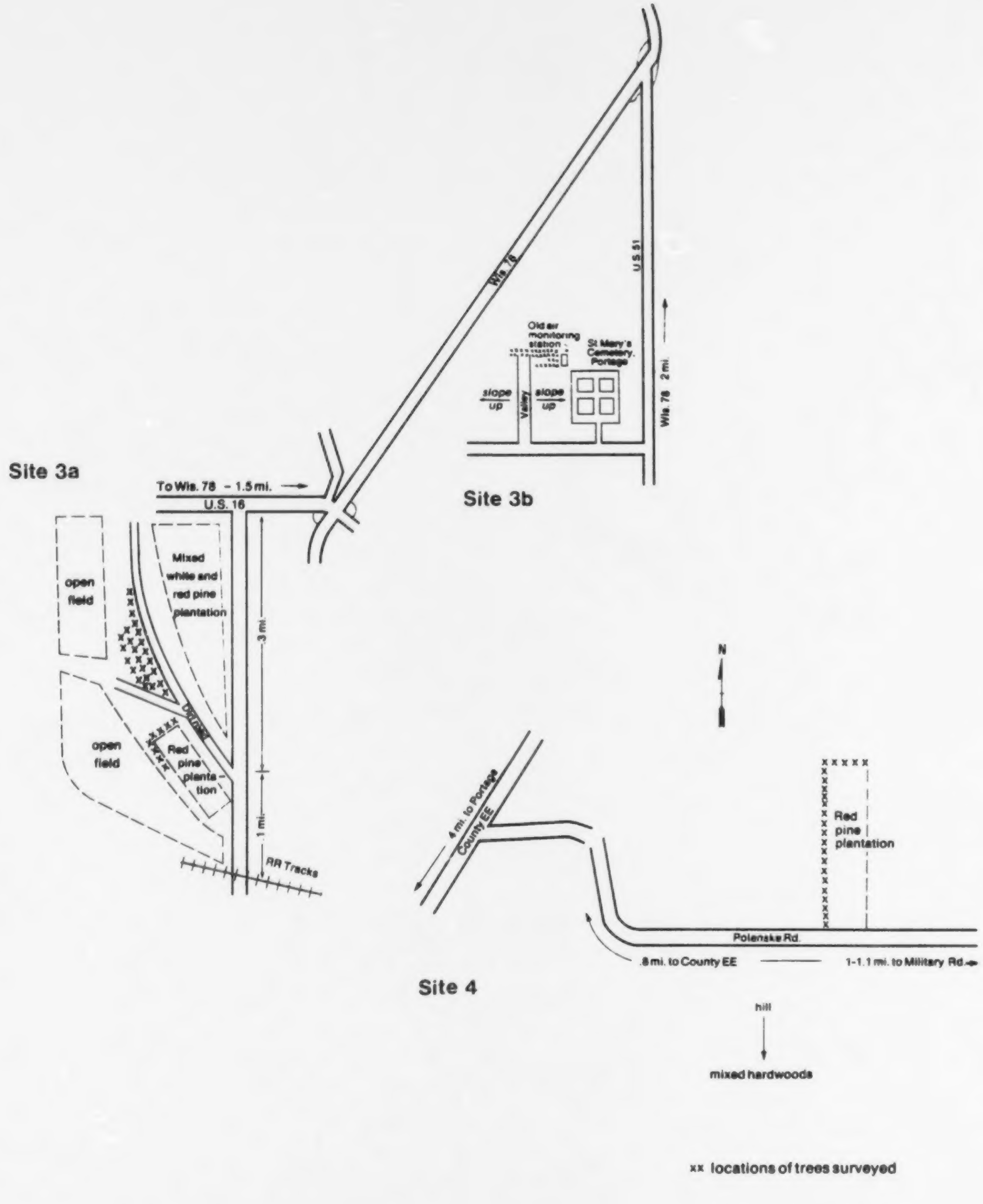
LOCATION OF SAMPLED WHITE PINE TREES AT EACH LOCATION

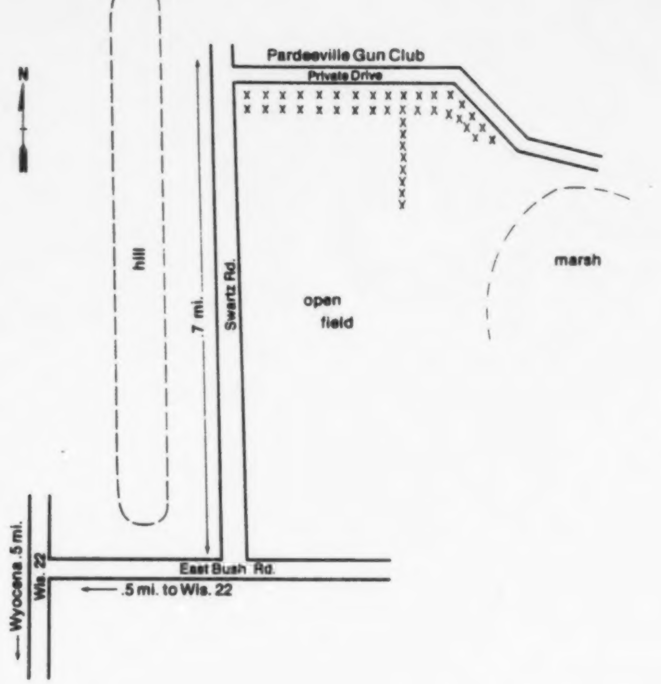

N
Mckenzie Environmental Center
Admin. Bldg.
County Q
Dirt road
open field
alfalfa field
forest
Mixed white and red pine plantation
forest
Pheasant Pens
U.S. 51 .2 mi.
line of hardwood trees
County CS and Q
Parking lot
DNR Park
Spruce-variety test planting
gentle slope upward
County CS
Site 1a
Site 1b


N
Driveway
Olson Rd.
White pine
Red pine
Spruces
Red Pine
Scattered Spruces
County CS
2 mi. to I90-94

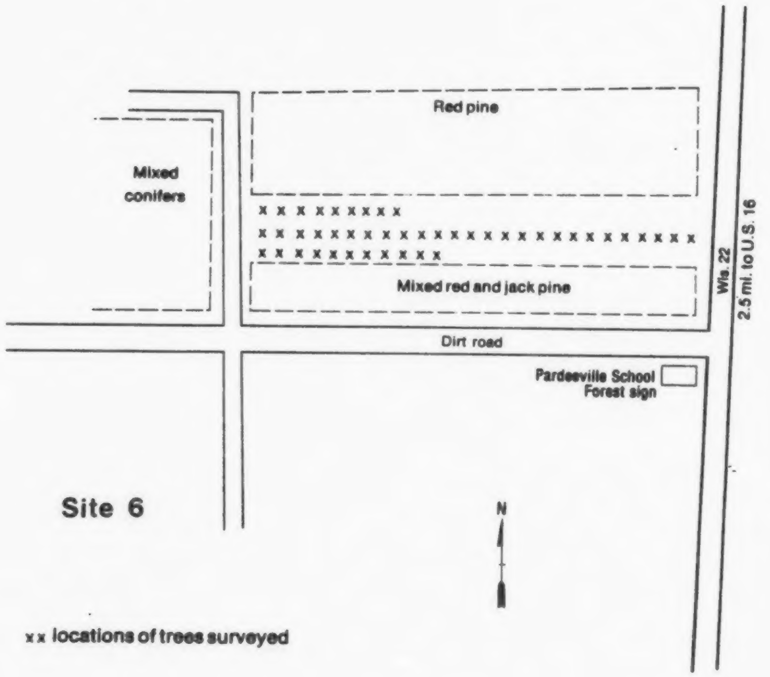
Site 2

ϕ telephone pole
x x locations of trees surveyed


Site 3a
To Wis. 78 - 1.5 mi.
U.S. 16
open field
Mixed white and red pine plantation
open field
Red pine planta-tion
3 mi.
1 mi.
RR Tracks
Wis. 78
U.S. 51
Old air monitoring station
St Mary's Cemetery, Portage
slope up
Valley
slope up
Wis. 78 2 mi.
Site 3b
N
4 mi. to Portage
County EE
Red pine plantation
Polenske Rd.
.8 mi. to County EE
1-1.1 mi. to Military Rd.
Site 4
hill
mixed hardwoods
xx locations of trees surveyed

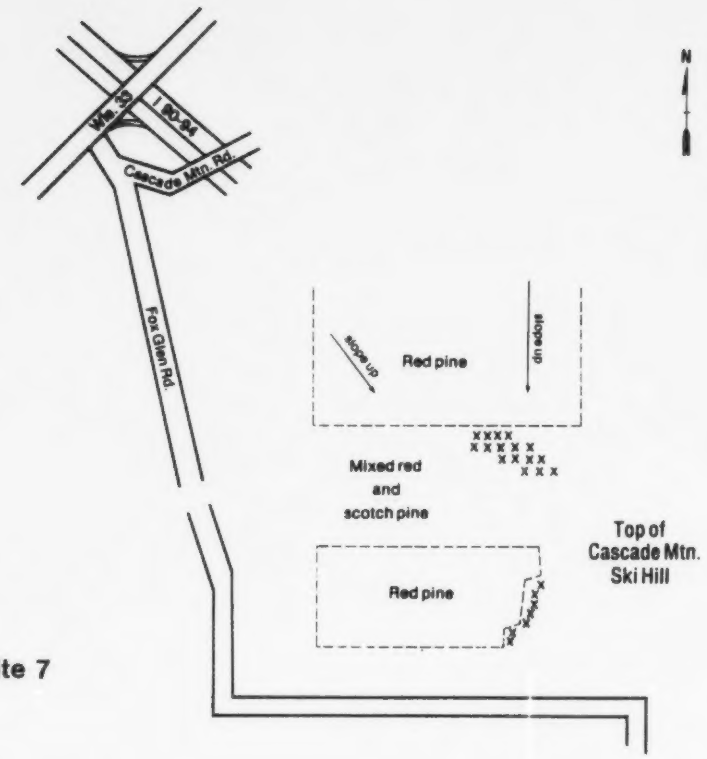

N
hill
7 mi.
Swartz Rd.
Pardeeville Gun Club
Private Drive
open
field
marsh
East Bush Rd.
.5 mi. to Wis. 22
Wis. 22
Wyocena .5 mi.

Site 5

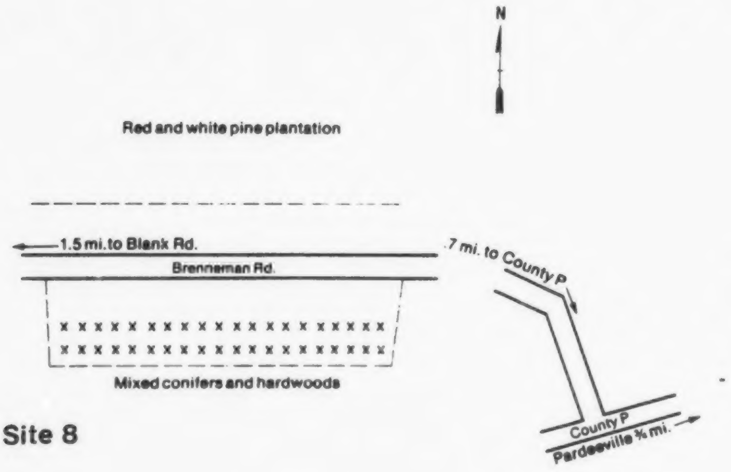

Red pine
Mixed conifers
Mixed red and jack pine
Wis. 22
2.5 mi. to U.S. 16
Dirt road
Pardeeville School
Forest sign
N

Site 6

xx locations of trees surveyed

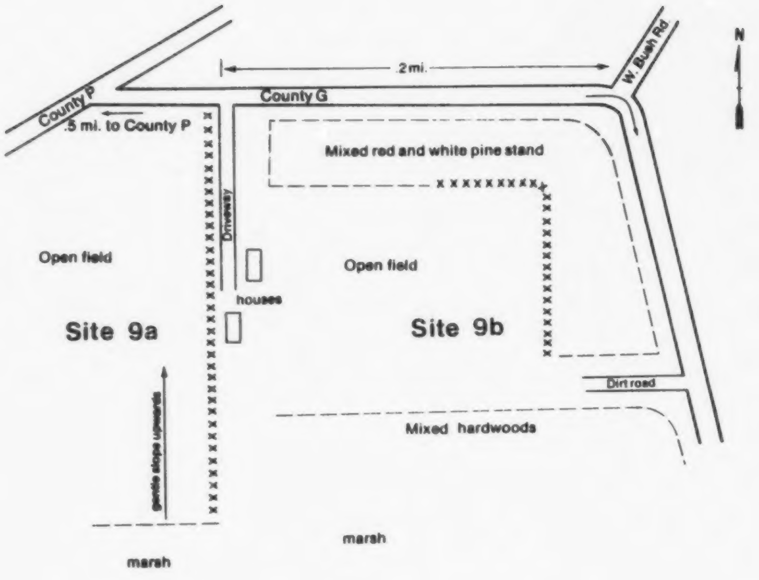

Wis. 33
I 90-94
Cascade Mtn. Rd.
Fox Glen Rd.
N
slope up
Red pine
slope up
Mixed red
and
scotch pine
Top of
Cascade Mtn.
Ski Hill
Red pine

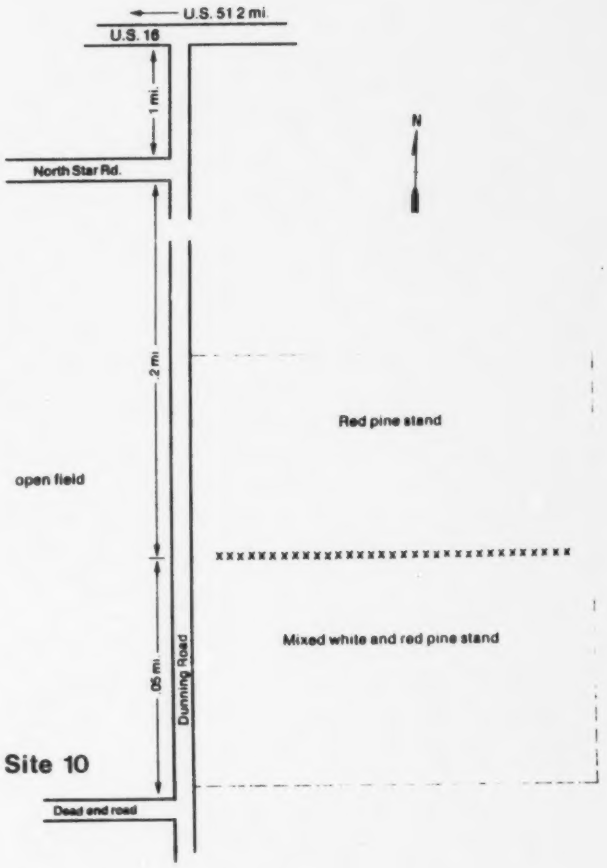
Site 7


N
Red and white pine plantation
1.5 mi. to Blank Rd.
Brenneman Rd.
.7 mi. to County P
Mixed conifers and hardwoods
County P
Pardeeville ¾ mi.

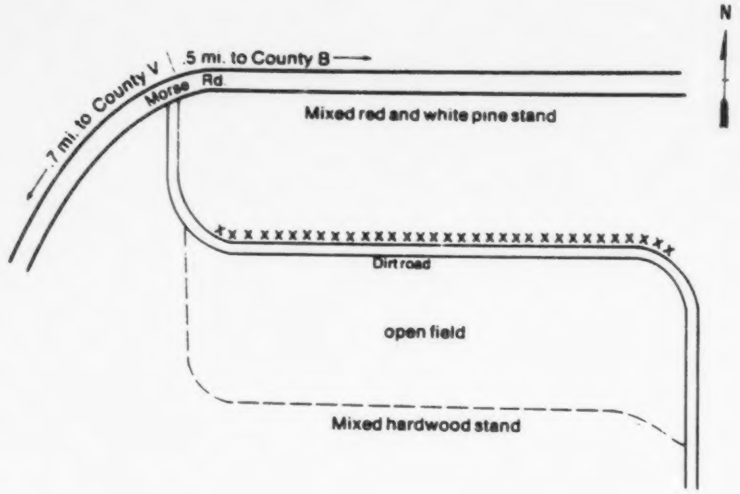
Site 8

xx locations of trees surveyed

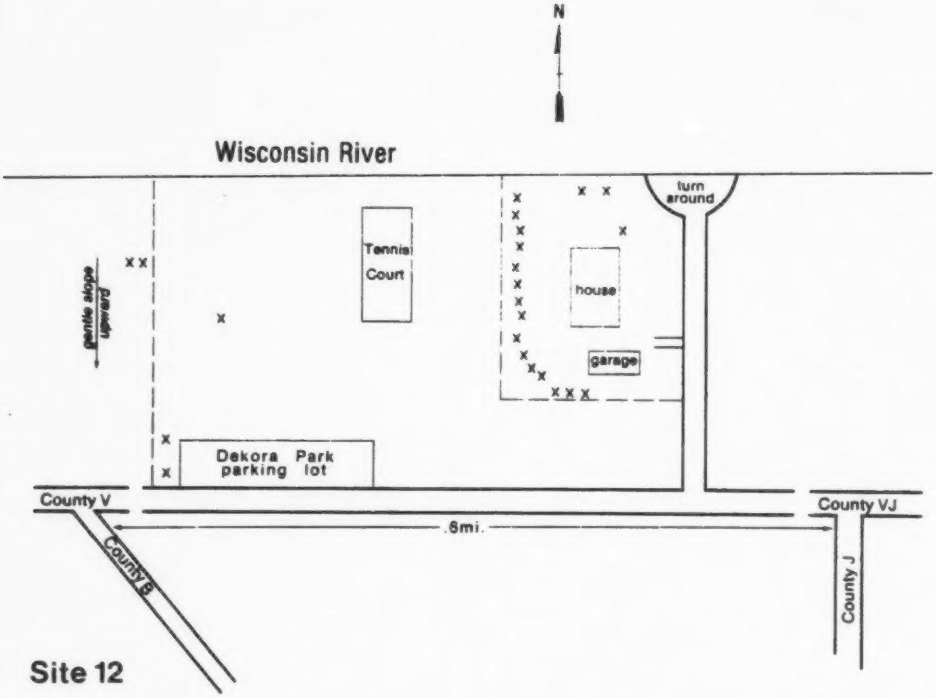

County P
.5 mi. to County P
County G
2 mi.
W. Bush Rd
N
Mixed red and white pine stand
Driveway
Open field
houses
Open field
Site 9a
Site 9b
Dirt road
gentle slope upwards
Mixed hardwoods
marsh
marsh


U.S. 51 2 mi.
U.S. 16
1 mi.
North Star Rd.
N
.2 mi.
Red pine stand
open field
Mixed white and red pine stand
.05 mi.
Dunning Road
Site 10
Dead end road

xx locations of trees surveyed

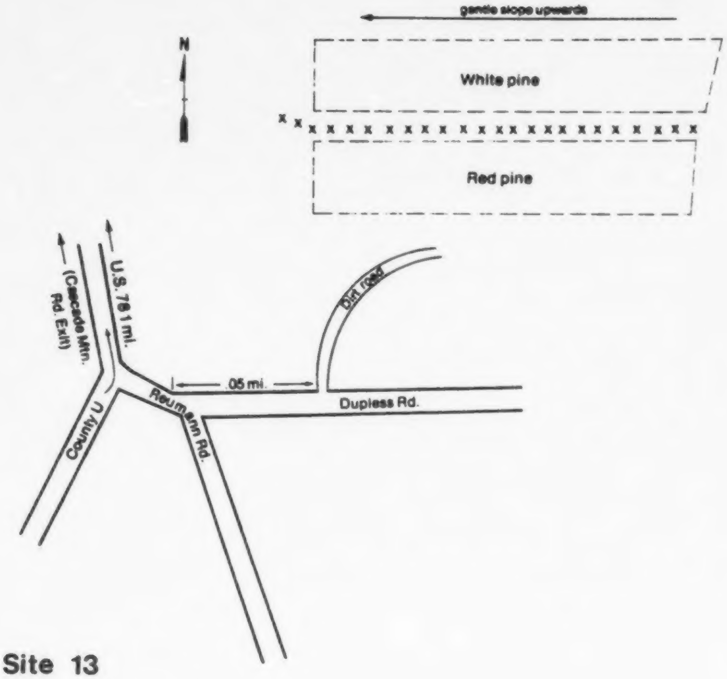

N
.7 mi. to County V
.5 mi. to County B
Morse Rd.
Mixed red and white pine stand
Dirt road
open field
Mixed hardwood stand

Site 11

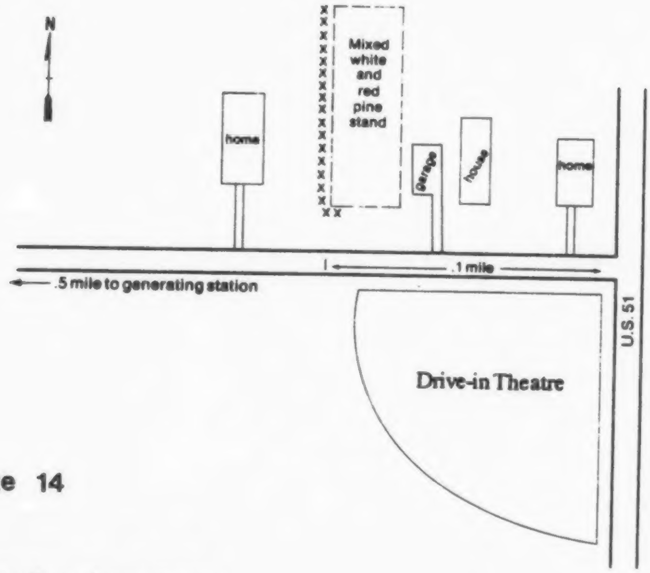

N
Wisconsin River
turn around
gentle slope upward
Tennis Court
house
garage
Dekora Park parking lot
County V
County B
.6mi.
County VJ
County J

Site 12

xx locations of trees surveyed

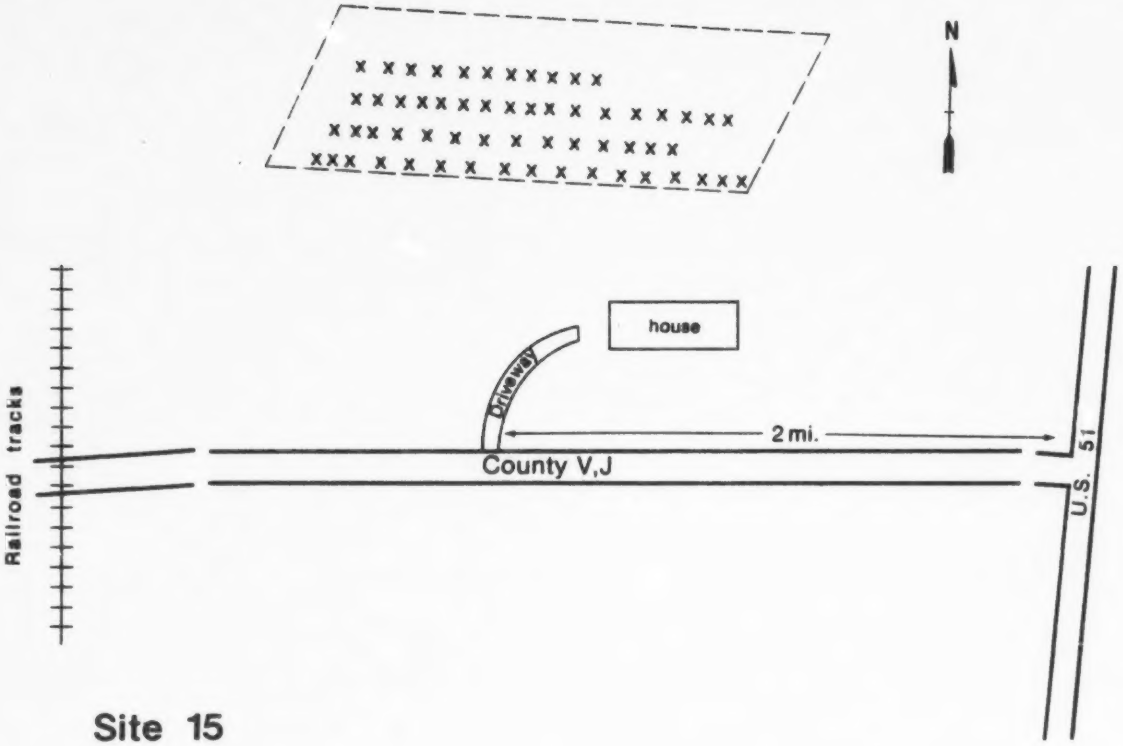

gentle slope upwards
N
White pine
Red pine
U.S. 78 1 mi.
(Cascade Mtn. Rd. Exit)
Dirt road
.05 mi.
Dupless Rd.
Reumann Rd.
County U

Site 13


N
Mixed white and red pine stand
home
garage
house
home
.1 mile
.5 mile to generating station
U.S. 51
Drive-in Theatre

Site 14

xx locations of trees surveyed


N
house
Driveway
2 mi.
County V,J
U.S. 51
Railroad tracks

Site 15

x x locations of trees surveyed

APPENDIX C

TREE DATA SUMMARIES

Legend

No. Pts. = The number of sample plots containing each separate tree species (20 plots at each site).

No. Trees = The number of trees larger than 15 cm in diameter at each site in the 20 sample plots.

BA = Total basal area of all trees larger than 15 cm in diameter at each site in the 20 sample plots.

% F = The number of sample plots at which a tree species occurred divided by the summed number of sample plots at which each tree species occurred.

% D = The number of trees of a species divided by the total number of trees sampled at each site.

% Do = The summed basal area of all sampled trees of a species divided by the summed basal area of all trees sampled at each site.

$$\text{I.V.} = \frac{\%\ F + \%\ D + \%\ Do}{3}$$

C.A.V. = The climax adaptation value established for each tree species (Curtis 1959). These are as follows:

Acer negundo	1.0
Acer rubrum	7.0
Acer saccharum	10.0
Carya ovata	4.5
Fraxinus americana	6.5
Juglans cinerea	7.5
Morus rubra	3.5
Ostrya virginiana	8.5
Populus grandidentata	4.5
P. tremuloides	1.0
Prunus serotina	3.5
Quercus alba	3.5
Q. ellipsoidalis	1.0
Q. macrocarpa	1.0
Q. borealis	5.5
Q. velutina	2.5
Tilia americana	7.5
Ulmus americana	7.5
Ulmus rubra	8.0

C.I. = I.V. x C.A.V.

TREE DATA SUMMARY SHEET

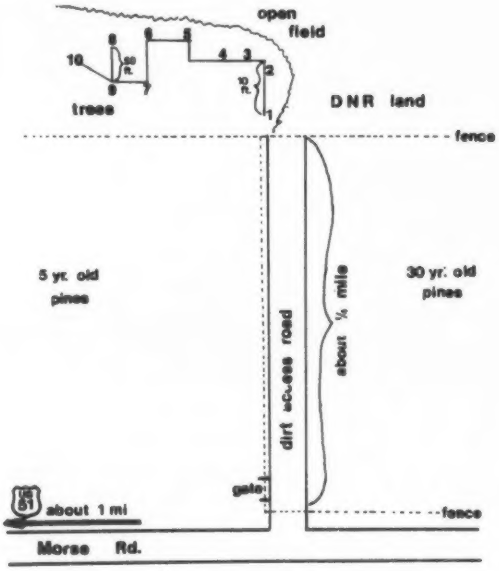
Site 1 DNR property
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% DO	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata	2	2	32	5.4	3.2	0.5	3.0	4.5	13.5
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina	10	25	1301	27.0	39.7	20.5	29.1	3.5	101.85
Quercus alba	6	8	1905	16.2	12.7	30.7	19.9	3.5	69.6
Q. ellipsoidalis								1.0	
Q. macrocarpa	13	20	1358	35.1	31.8	21.4	29.4	1.0	29.4
Q. borealis								5.5	
Q. velutina	6	8	1705	16.2	12.7	26.9	18.6	2.5	46.5
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	37	63	5346	99.9	100.1	100.0			260.8

Columbia County

Site 1 T11N, R9E, Sec 1
Public land

Tree No.	Basal Area, in.^{2}
1	220
2	150
3	270
4	250
5	130
6	300
7	235
8	160
9	240
10	380


open field
10
8
6
5
4
3
2
1
9
7
50 ft.
10 ft.
trees
DNR land
fence
5 yr. old pines
dirt access road
about ½ mile
30 yr. old pines
gate
US 51
about 1 mi
fence
Morse Rd.

TREE DATA SUMMARY SHEET

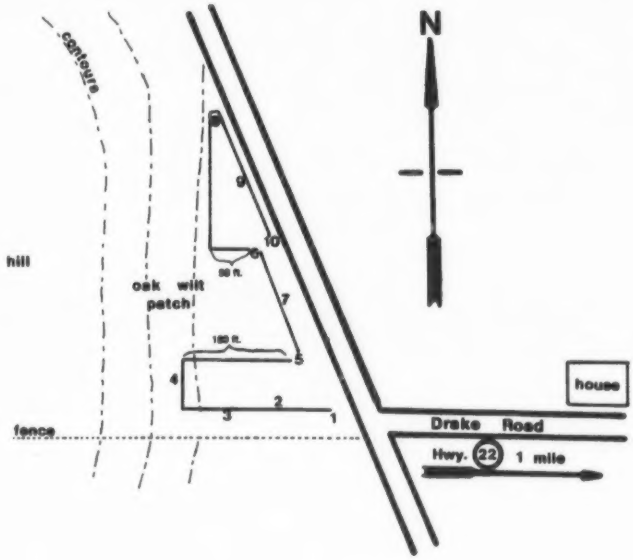
Site 2 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum	5	12	629	12.5	17.6	9.0	13.0	7.0	91.0
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina	6	10	344	15.0	14.7	4.9	11.5	3.5	40.2
Quercus alba	15	25	2943	37.5	36.8	42.0	38.8	3.5	135.8
Q. ellipsoidalis								1.0	
Q. macrocarpa	2	3	265	5.0	4.4	3.8	4.4	1.0	4.4
Q. borealis								5.5	
Q. velutina	12	18	2828	30.0	26.5	40.4	32.3	2.5	80.8
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	40	68	7002	100.0	100.0	100.1			352.2

Columbia County

Site 2 T11N, R10E, Sec 7
Private land

Tree No.	Basal Area, in.^{2}
11	200
12	150
13	290
14	190
15	180
16	180
17	150
18	310
19	200
20	360


contours
N
hill
oak wilt patch
8
9
10
6
30 ft.
7
180 ft.
5
4
3
2
1
fence
house
Drake Road
Hwy. 22 1 mile

TREE DATA SUMMARY SHEET

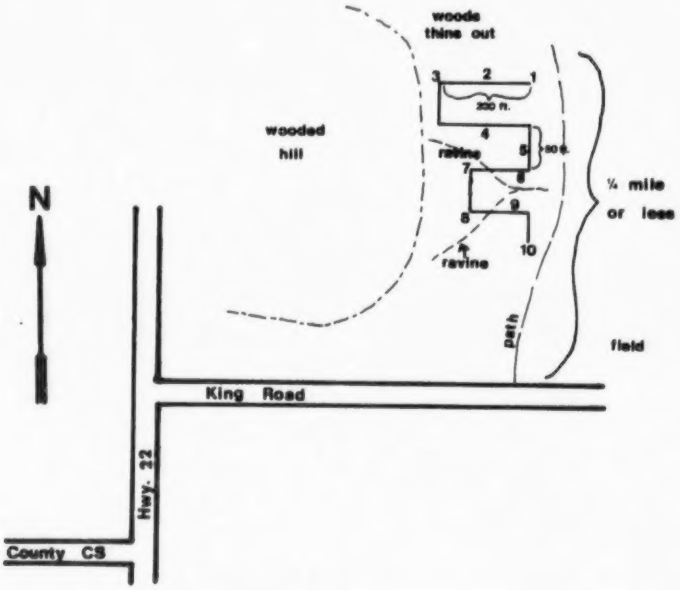
Site 3 Mud Lake SW DNR Property
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina	3	6	109	9.4	9.4	1.3	6.7	3.5	23.4
Quercus alba	17	41	4650	53.1	64.1	56.9	58.0	3.5	203.0
Q. ellipsoidalis								1.0	
Q. macrocarpa	2	2	89	6.2	3.1	1.1	3.5	1.0	3.5
Q. borealis								5.5	
Q. velutina	10	15	3325	31.2	23.4	40.7	31.8	2.5	79.5
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	32	64	8173						309.4

Columbia County

Site 3 T11N, R10E, Sec 21
Public land

Tree No.	Basal Area, in.^{2}
21	150
22	180
23	220
24	290
25	320
26	185
27	300
28	225
29	170
30	210


woods
thins out
3
2
1
200 ft.
wooded
hill
4
ravine
5
50 ft.
7
6
9
8
10
ravine
¼ mile
or less
N
path
field
King Road
Hwy. 22
County CS

TREE DATA SUMMARY SHEET

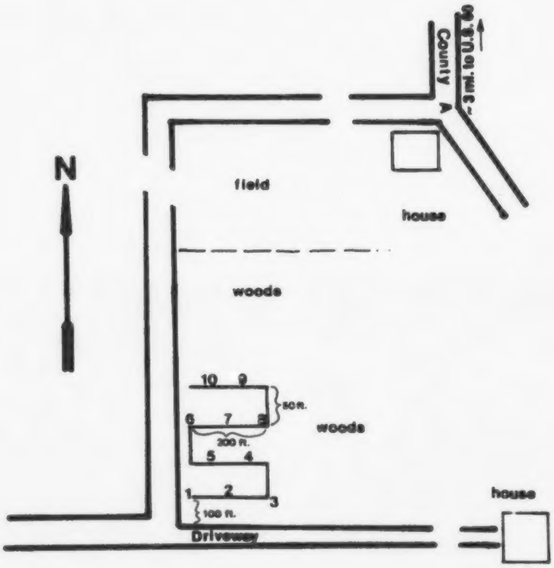
Site 4 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum	2	2	670	7.1	6.2	9.4	7.6	7.0	53.2
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina	1	1	220	3.6	3.1	3.1	3.3	3.5	11.5
Quercus alba	11	14	3195	39.3	43.8	44.7	42.6	3.5	149.1
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis								5.5	
Q. velutina	7	8	2850	25.0	25.0	39.9	30.0	2.5	75.0
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra	7	7	214	25.0	21.9	3.0	16.6	8.0	132.8
TOTALS	28	32	7149						421.6

Columbia County

Site 4 T10N, R11E, Sec 36
Private land

Tree No.	Basal Area, in.^{2}
31	240
32	525
33	180
34	350
35	270
36	430
37	470
38	560
39	270
40	260


~3 mi. U.S. 60
County A
N
field
house
woods
10
9
50 ft.
6
7
8
woods
200 ft.
5
4
1
2
3
100 ft.
Driveway
house

TREE DATA SUMMARY SHEET

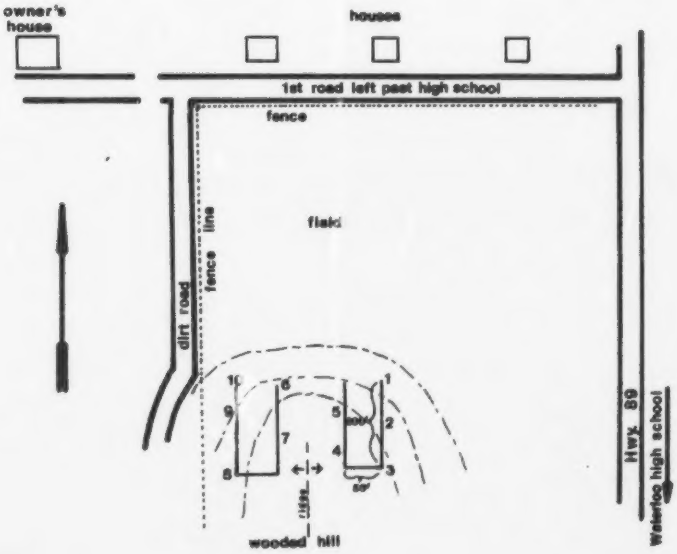
Site 5 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo	2	3	165	3.9	4.0	2.3	3.4	1.0	3.4
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.	2	2	35	3.9	2.6	.5	2.3	6.5	15.0
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi								4.5	
P. tremuloides								1.0	
Prunus serotina	7	13	599	13.7	17.1	8.2	1.3	3.5	45.5
Quercus alba	6	11	1240	11.8	14.5	17.0	14.4	3.5	
Q. ellipsoidalis								1.0	
Q. macrocarpa	1	1	14	2.0	1.3	0.2	1.2	1.0	1.2
Q. borealis								5.5	
Q. velutina	9	11	2550	17.6	14.5	35.0	22.4	2.5	56.0
Tilia americana	1	1	70	2.0	1.3	1.0	1.4	7.5	10.5
Ulmus americana								7.5	
Ulmus rubra	3	3	97	5.9	4.0	1.3	3.7	8.0	29.6
Acer saccharinum	4	4	465	7.8	5.3	6.4	6.5	4.0	26.0
Robinia pseudoacacia	13	24	1904	25.5	31.6	36.2	27.8	1.0	27.8
Celtis occidentalis	3	3	143	5.9	4.0	2.0	4.0	8.0	32.0
TOTALS	51	76	7282						247

Jefferson County

Site 5 T8N, R13E. Sec 6
Private land

Tree No.	Basal Area, in.^{2}
41	190
42	290
43	215
44	280
45	240
46	200
47	155
48	270
49	280
50	205


owner's house
houses
1st road left past high school
fence
fence line
field
dirt road
1
2
3
4
5
6
7
8
9
10
ridge
50'
wooded hill
Hwy. 89
Waterloo high school

TREE DATA SUMMARY SHEET

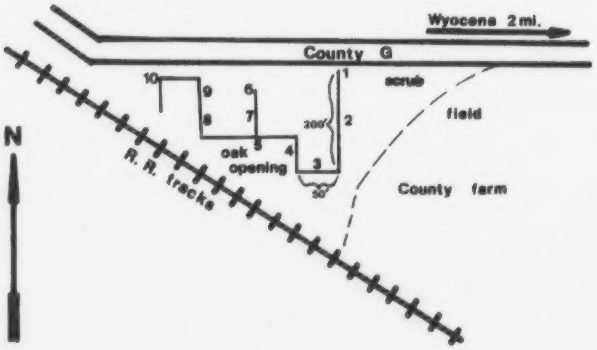
Site 7 Columbia County Farm
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina								3.5	
Quercus alba	2	2	101	16.7	8.7	2.1	9.2	3.5	32.2
Q. ellipsoidalis								1.0	
Q. macrocarpa	1	2	1645	8.3	8.7	33.7	16.9	1.0	16.9
Q. borealis								5.5	
Q. velutina	9	19	3134	75.0	82.6	64.2	73.9	2.5	184.84
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	12	23	4880						233.9

Columbia County

Site 7 T12N, R10E, Sec 20
Public land

Tree No.	Basal Area, in.^{2}
61	190
62	150
63	125
64	160
65	250
66	245
67	145
68	175
69	250
70	290


Wyocena 2 mi.
County G
1
2
3
4
5
6
7
8
9
10
200'
50'
scrub
field
County farm
oak opening
R. R. tracks
N

TREE DATA SUMMARY SHEET

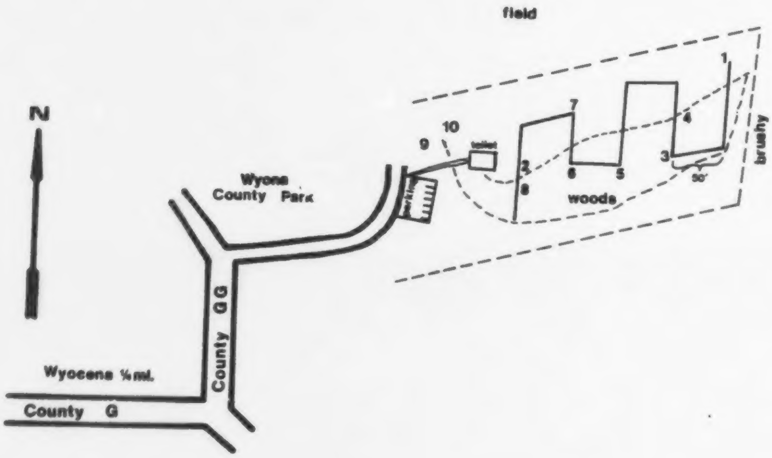
Site 8 Wyona County Park
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata	2	2	185	7.1	5.3	2.4	4.9	4.5	22.1
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.	2	5	204	7.1	13.2	2.6	7.6	4.5	35.2
P. tremuloides								1.0	
Prunus serotina	4	6	327	14.3	15.8	4.2	11.4	3.5	39.9
Quercus alba	8	9	3245	28.6	23.7	42.2	31.5	3.5	110.2
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis								5.5	
Q. velutina	12	16	3737	42.9	42.1	38.6	44.5	2.5	111.3
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	28	38	7698						317.7

Columbia County

Site 8 T12N, R10E, Sec 22
Public land

Tree No.	Basal Area, in.^{2}
71	520
72	240
73	320
74	350
75	190
76	250
77	270
78	430
79	280
80	460


field
N
1
7
4
10
9
toilet
2
3
8
6
5
50'
woods
brushy
Wyona
County Park
County GG
Wyocena ¼ mi.
County G

TREE DATA SUMMARY SHEET

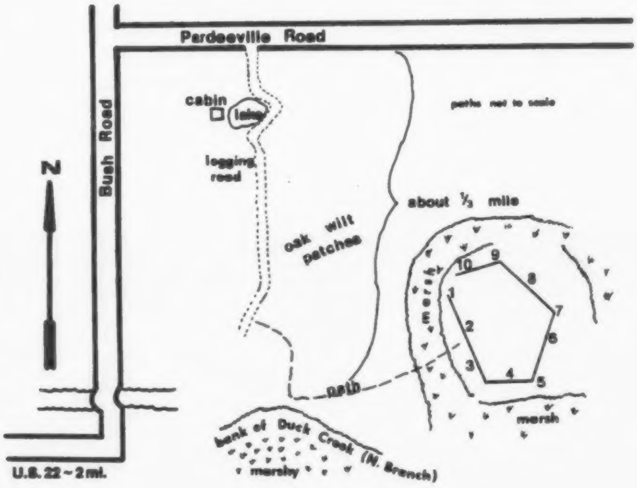
Site 9 Private land
12 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum	1	1	30	5.0	2.6	.7	2.8	7.0	19.6
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi								4.5	
P. tremuloides								1.0	
Prunus serotina	3	3	115	15.0	10.3	2.8	9.4	3.5	32.9
Quercus alba	4	10	535	20.0	25.6	12.8	19.5	3.5	68.2
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis								5.5	
Q. velutina	12	24	3487	60.0	61.5	83.7	68.4	2.5	171.0
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	20	39	4167						291.7

Columbia County

Site 9 T12N, R10E, NW ¼, Sec 13
Private land

Tree No.	Basal Area, in.^{2}
181	205
182	130
183	180
184	290
185	130
186	300
187	260
188	190
189	100
190	240


Pardeeville Road
Bush Road
N
cabin
lake
logging road
paths not to scale
about ⅓ mile
oak wilt patches
marsh
10
9
8
1
7
2
6
3
4
5
path
marsh
bank of Duck Creek (N. Branch)
marshy
U.S. 22 ~ 2 mi.

TREE DATA SUMMARY SHEET

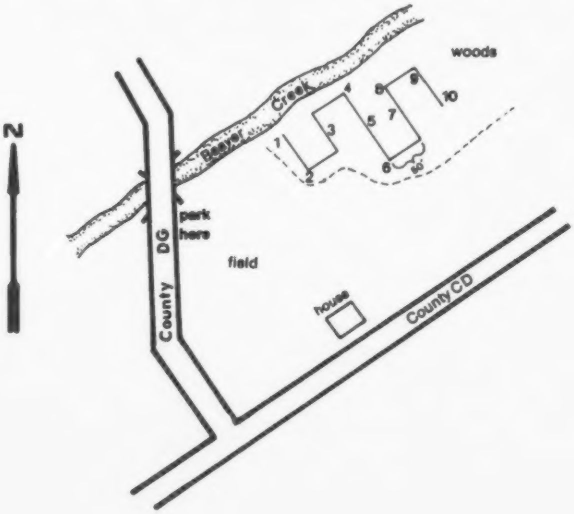
Site 10 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi								4.5	
P. tremuloides								1.0	
Prunus serotina	1	1	120	4.2	2.0	1.3	2.5	3.5	8.8
Quercus alba	4	5	323	16.7	12.5	3.6	10.9	3.5	38.2
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis								5.5	
Q. velutina	17	31	7385	70.8	77.5	82.4	76.9	2.5	192.2
Tilia americana	2	3	1130	8.3	7.5	12.6	9.5	7.5	71.2
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	24	40	8958						310.4

Columbia County

Site 10 T12N, R12E, Sec 24
Private land

Tree No.	Basal Area, in.^{2}
91	290
92	250
93	200
94	190
95	190
96	185
97	200
98	310
99	160
100	165


N
woods
Beaver Creek
1
2
3
4
5
6
7
8
9
10
50'
park here
County DG
field
house
County CD

TREE DATA SUMMARY SHEET

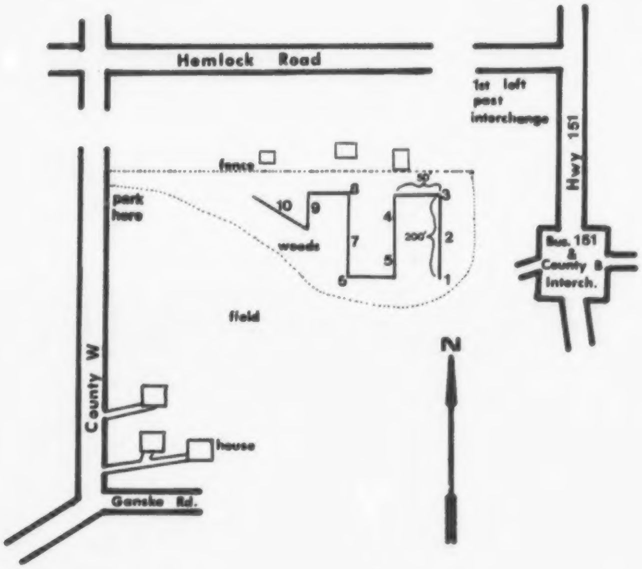
Site 11 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.	31	2	48	2.8	3.4	.6	2.3	4.5	10.4
P. tremuloides								1.0	
Prunus serotina	16	34	1144	44.4	57.6	14.2	38.7	3.5	135.4
Quercus alba	10	12	3050	27.8	20.3	38.0	28.7	3.5	100.4
Q. ellipsoidalis								1.0	
Q. macrocarpa	2	2	610	5.6	3.4	7.6	5.5	1.0	5.5
Q. borealis								5.5	
Q. velutina	7	9	3180	19.4	15.2	39.6	24.7	2.5	61.8
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	36	59	8032						313.5

Dodge County

Site 11 T12N, R14E, Sec 21
Private land

Tree No.	Basal Area, in.^{2}
101	230
102	340
103	270
104	430
105	295
106	310
107	410
108	350
109	390
110	280


Hemlock Road
1st left
past
interchange
Hwy 151
Bus. 151
&
County B
Interch.
fence
50'
park
here
10
9
8
3
4
2
200'
7
5
6
1
woods
field
N
County W
house
Ganske Rd.

TREE DATA SUMMARY SHEET

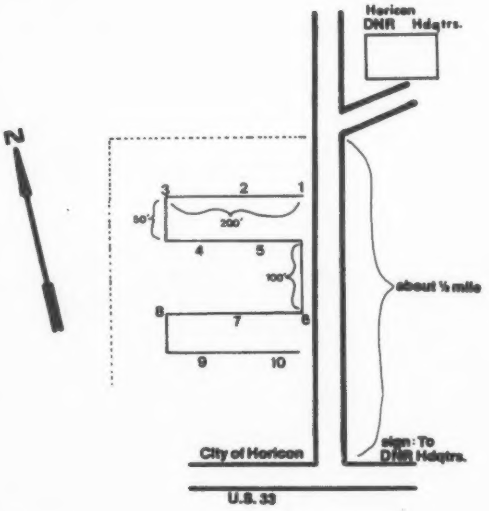
Site 12 Horicon wildlife area
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata	2	3	257	3.4	3.6	3.1	3.4	4.5	34
Fraxinus amer.								6.5	
Juglans cinerea	16	29	2028	27.1	34.5	24.3	28.6	7.5	185.9
Morus rubra								3.5	
Ostrya virginiana	7	11	534	11.9	13.3	6.4	10.5	8.5	89.2
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina	10	20	1219	17.0	23.8	14.6	18.5	3.5	64.8
Quercus alba	4	4	695	6.8	4.8	8.3	6.6	3.5	23.1
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis	3	6	1500	5.1	7.1	18.00	10.1	5.5	55.6
Q. velutina								2.5	
Tilia americana	13	16	1899	22.0	19.0	22.7	21.2	7.5	159
Ulmus americana	4	5	218	6.8	6.0	2.6	5.1	7.5	38.2
Ulmus rubra								8.0	
TOTALS	59	84	8350						649.8

Dodge County

Site 12 T12N, R16E, Sec 19
Public land

Tree No.	Basal Area, in.^{2}
111	130
112	500
113	300
114	300
115	280
116	340
117	270
118	170
119	230
120	450


Horicon
DNR Hdqtrs.
N
3
2
1
50'
200'
4
5
100'
about ½ mile
8
7
6
9
10
City of Horicon
sign: To
DNR Hdqtrs.
U.S. 33

TREE DATA SUMMARY SHEET

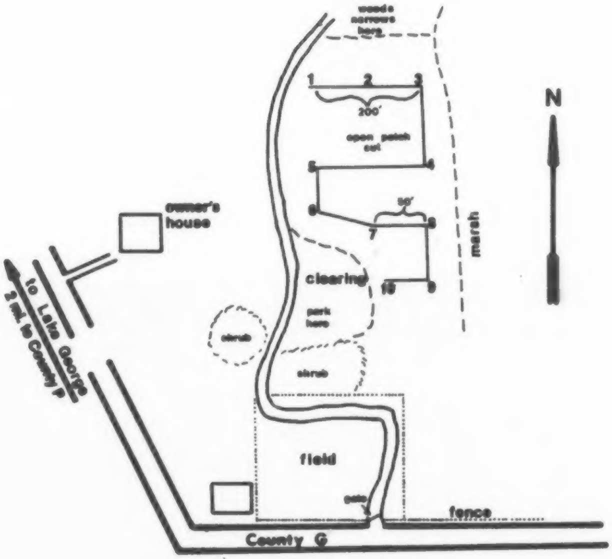
Site 13		Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina								3.5	
Quercus alba	11	28	3750	45.8	57.1	56.0	53.0	3.5	185.5
Q. ellipsoidalis	12	20	2860	50.0	40.8	42.7	44.5	1.0	44.5
Q. macrocarpa	1	1	80	4.2	2.0	1.2	2.5	1.0	2.5
Q. borealis								5.5	
Q. velutina								2.5	
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	24	49	6698						232.5

Columbia County

Site 13		T12N, R9E, Sec 24
Private land

Tree No.	Basal Area, in.^{2}
121	190
122	140
123	120
124	170
125	120
126	190
127	250
128	120
129	150
130	120


woods narrows here
1
2
3
200'
open patch cut
5
4
N
6
50'
8
7
owner's house
marsh
clearing
10
9
park here
to Lake George
2 mi. to County P
shrub
shrub
field
gate
fence
County G

TREE DATA SUMMARY SHEET

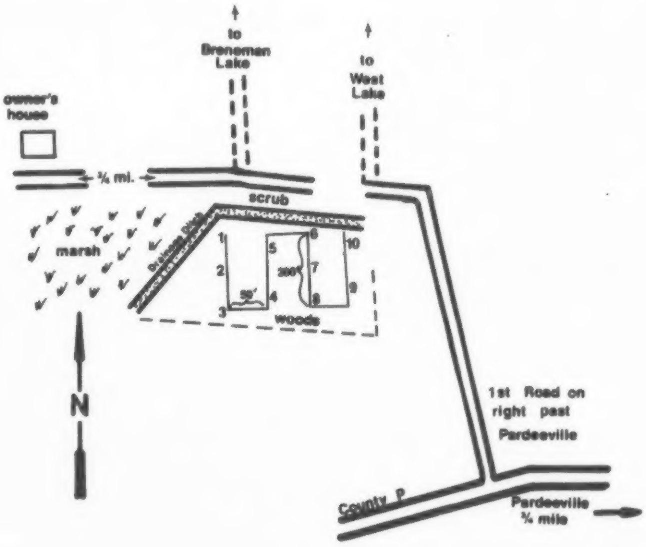
Site 14 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.	2	2	205	5.0	2.5	2.4	3.3	4.5	14.8
P. tremuloides								1.0	
Prunus serotina	3	7	505	7.5	8.9	5.9	7.4	3.5	25.9
Quercus alba	16	29	2599	40.0	36.7	30.6	35.8	3.5	125.3
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis								5.5	
Q. velutina	18	40	4820	45.0	50.6	56.7	50.8	2.5	127
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
Acer saccharinum	1	1	370	2.5	1.3	4.4	2.7	4.0	10.8
TOTALS	40	79	8499						303.8

Columbia County

Site 14 T12N, R10E, N ½, Sec 5
Private land

Tree No.	Basal Area, in.^{2}
131	150
132	110
133	170
134	150
135	130
136	105
137	125
138	180
139	130
140	175


to Breneman Lake
to West Lake
owner's house
¾ mi.
scrub
marsh
Drainage Ditch
1
2
3
4
5
6
7
8
9
10
50'
200'
woods
N
1st Road on right past Pardeeville
County P
Pardeeville ¾ mile

TREE DATA SUMMARY SHEET

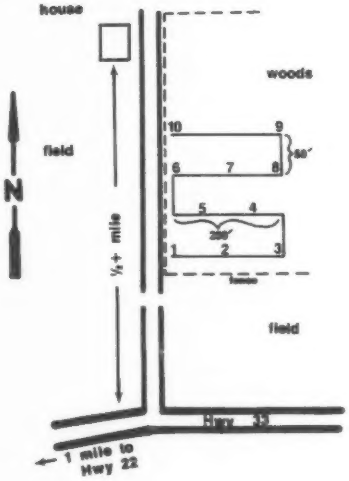
Site 15 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata	5	9	865	10.4	10.8	8.9	10.0	4.5	45.0
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina	3	3	260	6.2	3.6	2.7	4.2	3.5	14.7
Quercus alba	13	28	3692	27.1	33.7	37.8	32.9	3.5	115.2
Q. ellipsoidalis								1.0	
Q. macrocarpa	2	3	790	4.2	3.6	8.1	5.3	1.0	5.3
Q. borealis								5.5	
Q. velutina	16	27	3690	33.3	32.5	37.8	34.5	2.5	86.2
Tilia americana								7.5	
Ulmus americana	9	13	464	18.8	15.7	4.8	13.1	7.5	98.2
Ulmus rubra								8.0	
TOTALS	48	83	9761						364.6

Columbia County

Site 15 T13N, R10E, Sec 23
Private land

Tree No.	Basal Area, in.^{2}
141	150
142	175
143	120
144	140
145	240
146	205
147	120
148	170
149	170
150	165



TREE DATA SUMMARY SHEET

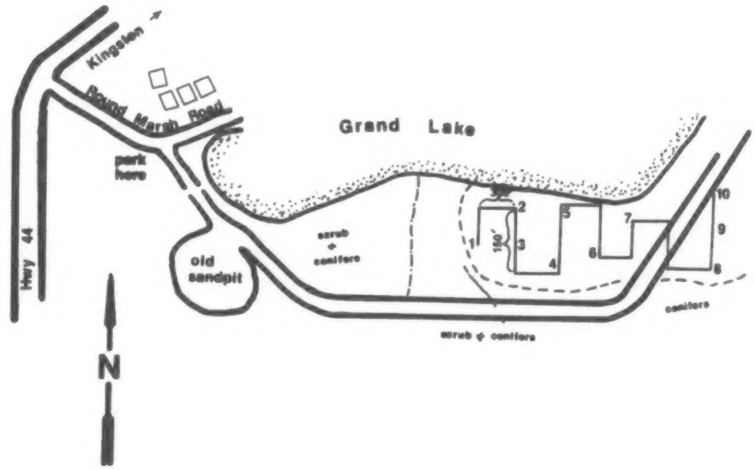
Site 16 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI.
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina								3.5	
Quercus alba	9	14	1110	26.5	25.9	13.1	21.8	3.5	76.3
Q. ellipsoidalis								1.0	
Q. macrocarpa	6	9	630	17.6	16.7	7.4	13.9	1.0	13.9
Q. borealis								5.5	
Q. velutina	16	28	6680	47.1	51.8	79.0	59.3	2.5	
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
Pinus strobus	1	1	14	2.9	1.8	0.2	1.6	5.0	8
Juniperus virginiana	2	2	26	5.9	4.7	0.4	3.3	1.0	3.3
TOTALS	34	54	8460						249.7

Green Lake County

Site 16 T14N, R11E, Sec 13
Private land

Tree No.	Basal Area, in.^{2}
151	140
152	280
153	190
154	155
155	180
156	420
157	200
158	225
159	280
160	160


Kingston
Round Marsh Road
park here
Hwy 44
old sandpit
Grand Lake
scrub & conifers
100'
1
2
3
4
5
6
7
8
9
10
conifers
scrub & conifers
N

TREE DATA SUMMARY SHEET

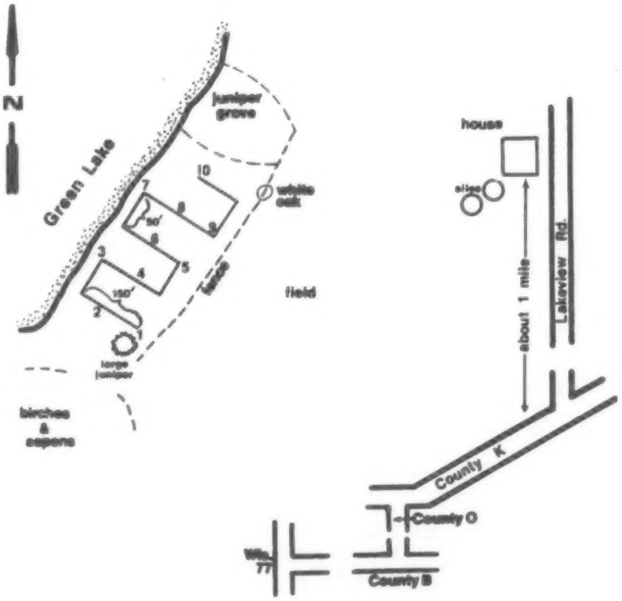
Site 17 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata	2	2	150	6.7	3.7	2.0	4.1	4.5	18.4
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina								3.5	
Quercus alba	6	8	910	20.0	14.8	11.9	15.6	3.5	54.6
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis	18	38	6410	60.0	70.4	83.7	71.4	5.5	392.7
Q. velutina								2.5	
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
Juniperus virginiana	1	2	24	3.3	3.7	0.3	2.4	1.0	2.4
Betula papyrifera	3	4	167	10.0	7.4	2.2	6.5	5.0	32.5
TOTALS	30	54	7661						500.6

Green Lake County

Site 17 T15N, R13E, Sec 6
Private land

Tree No.	Basal Area, in.^{2}
161	300
162	210
163	160
164	155
165	220
166	140
167	110
168	150
169	230
170	200


N
Green Lake
juniper grove
10
7
8
9
50'
6
3
4
5
150'
2
1
white oak
fence
field
large juniper
birches & aspens
house
silos
about 1 mile
Lakeview Rd.
County K
County O
Wis. 77
County B

TREE DATA SUMMARY SHEET

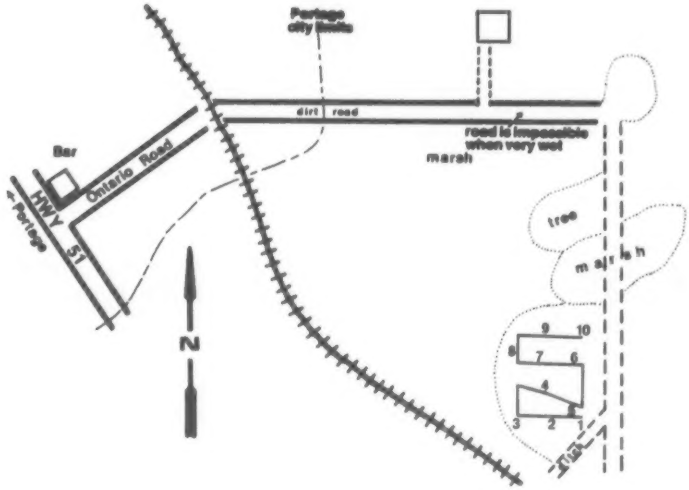
Site 19 DNR Property
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina	1	1	12	4.6	2.4	0.4	2.5	3.5	8.8
Quercus alba	5	8	650	22.7	19.5	19.0	20.4	3.5	71.4
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis								5.5	
Q. velutina	16	32	2768	72.7	78.0	80.7	77.1	2.5	192.8
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	23	41	3430						273

Columbia County

Site 19 T12N, R9E, Sec 10
Public land

Tree No.	Basal Area, in.^{2}
81	185
82	270
83	120
84	250
85	430
86	100
87	200
88	135
89	400
90	230


Portage city limits
dirt road
road is impassible when very wet
marsh
Bar
Ontario Road
HWY 51
← Portage
N
tree
marsh
9
10
8
7
6
4
5
3
2
1
trail

TREE DATA SUMMARY SHEET

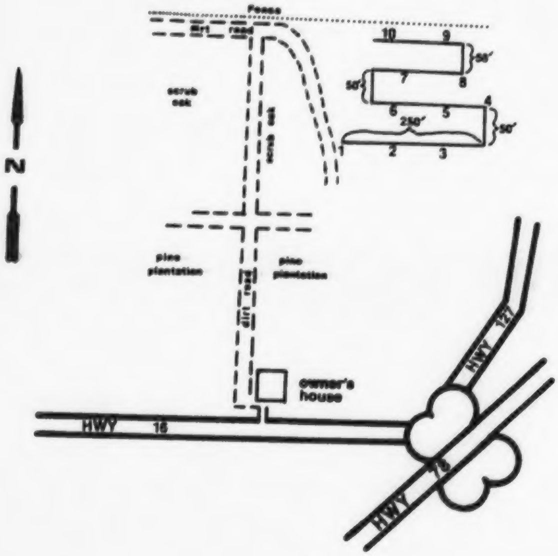
Site 20 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina	1	1	20	4.2	2.0	0.6	2.3	3.5	8.0
Quercus alba	3	4	425	12.5	8.0	12.1	10.9	3.5	38.2
Q. ellipsoidalis								1.0	
Q. macrocarpa	1	1	75	412	2.0	2.1	2.8	1.0	2.8
Q. borealis								5.5	
Q. velutina	18	43	2975	75.0	86.0	84.8	81.9	2.5	204.8
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
Robinia pseudoacacia	1	1	12	4.2	2.0	0.3	2.2	1.0	2.2
TOTALS	24	50	3507						256.0

Columbia County

Site 20 T13N, R8E, Sec 36
Private land

Tree No.	Basal Area, in.^{2}
191	220
192	190
193	110
194	125
195	290
196	110
197	135
198	135
199	200
200	265


N
Fence
dirt road
scrub oak
scrub oak
10
9
50'
7
8
50'
6
5
4
250'
50'
1
2
3
pine plantation
pine plantation
dirt road
owner's house
HWY 16
HWY 127
HWY 78

TREE DATA SUMMARY SHEET

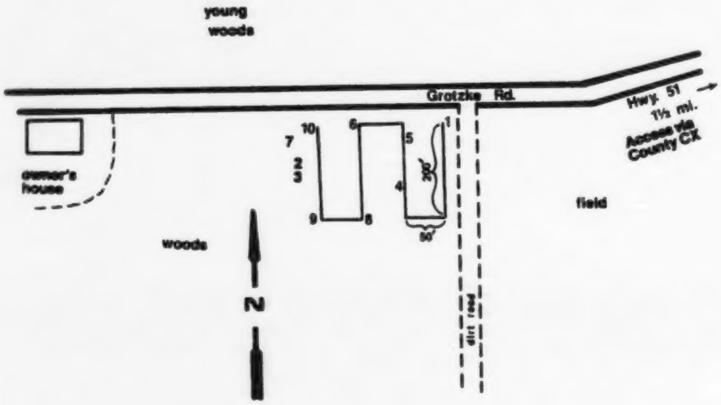
Site 21	Private land 20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrava virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina								3.5	
Quercus alba	18	68	3351	51.4	58.1	47.2	52.2	3.5	182.7
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis								5.5	
Q. velutina	17	49	3745	48.6	41.9	52.8	47.8	2.5	119.5
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	35	117	7096						302.2

Columbia County

Site 21	T13N, R8E, Sec 12 Private land

Tree No.	Basal Area, in.^{2}
201	140
202	185
203	150
204	135
205	170
206	150
207	110
208	110
209	140
210	155


young woods
Grotzke Rd.
Hwy. 51 →
1½ mi.
Access via County CX
owner's house
10
6
1
7
5
2
3
200'
4
9
8
50'
field
woods
N
dirt road

TREE DATA SUMMARY SHEET

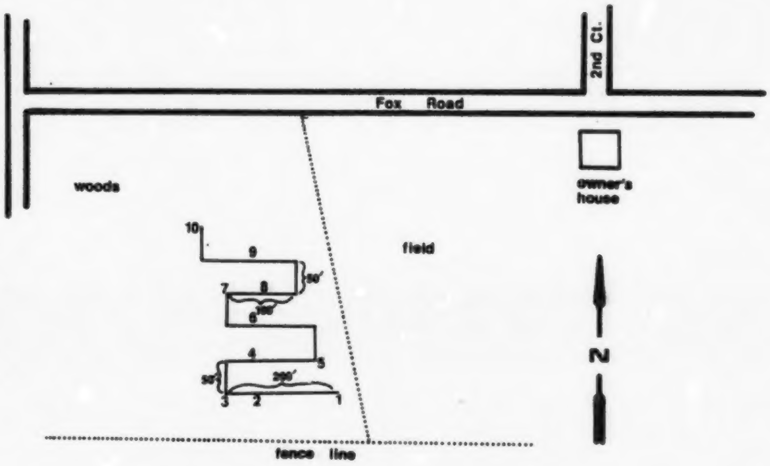
Site 22 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum	2	3	320	5.3	4.6	4.5	4.8	10.0	48.0
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina	7	14	512	18.4	21.2	7.1	15.6	3.5	54.6
Quercus alba	10	16	1076	26.3	24.2	15.0	21.8	3.5	76.3
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis								5.5	
Q. velutina	15	28	4942	39.5	42.4	68.8	50.2	2.5	125.5
Tilia americana								7.5	
Ulmus americana	4	5	330	10.5	7.6	4.6	7.6	7.5	57.0
Ulmus rubra								8.0	
TOTALS	38	66	7180						361.4

Marquette County

Site 22 T15N, R8E, Sec 29
Private land

Tree No.	Basal Area, in.^{2}
211	150
212	250 double tree
213	280
214	230 double tree
215	380
216	225 B&W pics have #218 on them
217	110
218	175 double tree B&W pics have #216 on them
219	305
220	260



TREE DATA SUMMARY SHEET

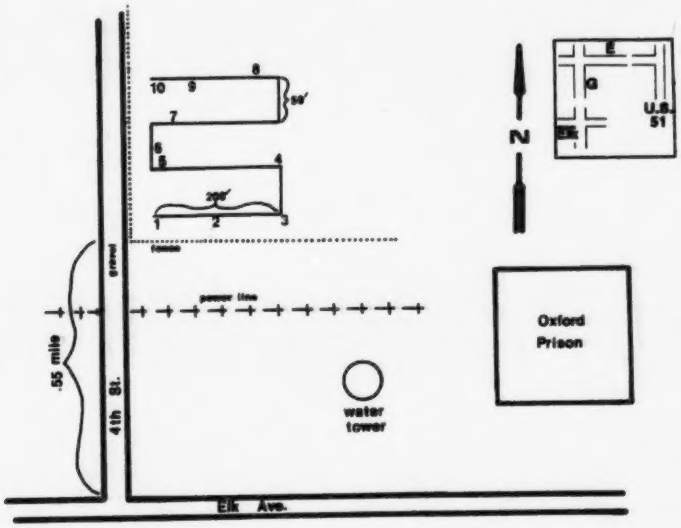
Site 23 Oxford prison
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina								3.5	
Quercus alba	9	16	736	31.0	18.8	13.8	21.2	3.5	74.2
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis								5.5	
Q. velutina	20	69	4602	69.0	81.2	86.2	78.8	2.5	197
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	29	85	5338						271.2

Adams County

Site 23 T15N, R7E, Sec 10
Restricted federal land

Tree No.	Basal Area, in.^{2}
221	290
222	145
223	130
224	125
225	105
226	100
227	105
228	100
229	140
230	125


10
9
8
50'
7
6
5
4
200'
1
2
3
fence
gravel
power line
.55 mile
4th St.
water tower
Oxford Prison
Elk Ave.
N
E
G
U.S. 51
Elk

TREE DATA SUMMARY SHEET

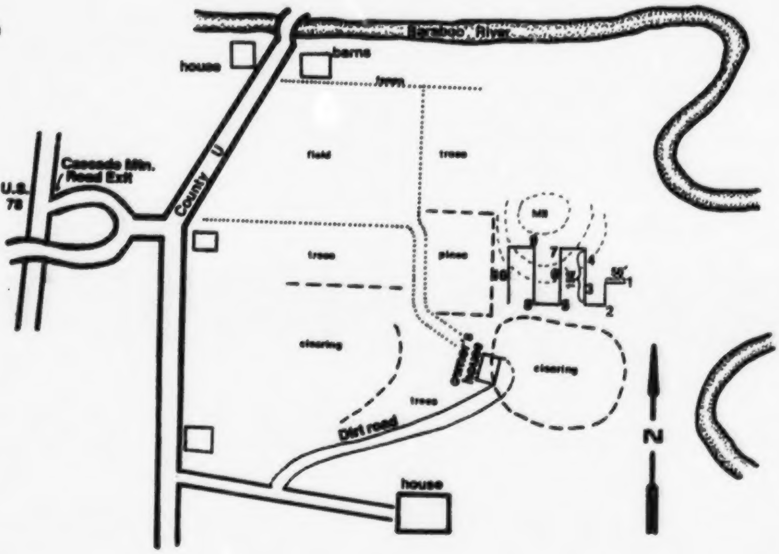
Site 25 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina								3.5	
Quercus alba								3.5	
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis								5.5	
Q. velutina	20	65	7770	100	100	100	100	2.5	250.0
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	20	65	7770						250.0

Columbia County

Site 25 T12N, R9E, Sec 30
Private land

Tree No.	Basal Area, in.^{2}
241	130
242	140
243	140
244	150
245	170
246	170
247	160
248	120
249	130
250	150


Baraboo River
house
barns
fence
field
trees
Cascade Mtn. Road Exit
U.S. 78
County U
hill
trees
pines
7
4
50'
1
3
2
clearing
clearing
trees
Dirt road
house
N

TREE DATA SUMMARY SHEET

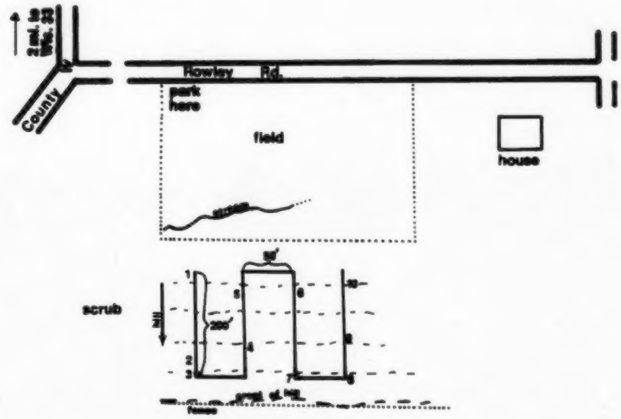
Site 26 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum	4	5	332	10.0	7.9	4.3	7.4	7.0	51.8
Acer saccharum								10.0	
Carya ovata	2	2	100	5.0	3.2	1.3	3.2	4.5	14.4
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina								3.5	
Quercus alba	15	28	2440	37.5	44.4	31.7	37.9	3.5	132.6
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis								5.5	
Q. velutina	16	25	4515	40.0	39.7	58.7	46.1	2.5	115.2
Tilia americana	2	2	265	5.0	3.2	3.4	3.9	7.5	29.2
Ulmus americana	1	1	35	2.5	1.6	0.5	1.5	7.5	11.2
Ulmus rubra								8.0	
TOTALS	40	63	7687						354.4

Columbia County

Site 26 T12N, R8E, Sec 27
Private land

Tree No.	Basal Area, in.^{2}
251	200
252	110
253	185
254	120
255	290
256	200
257	180
258	140
259	190
260	190


2 mi. to Wis. 33
Howley Rd.
County
park here
field
house
stream
50'
1
2
3
4
5
6
7
8
9
10
scrub
hill
200'
fence

TREE DATA SUMMARY SHEET

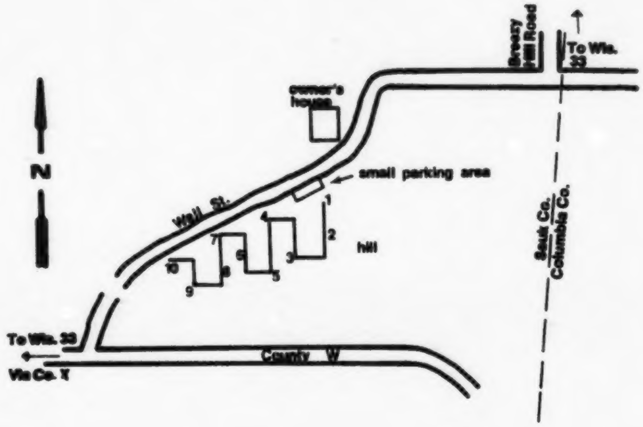
Site 27 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum	15	24	1382	30.0	32.9	16.5	26.5	10.0	265
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.	3	5	395	6.0	6.8	4.7	5.8	4.5	26.1
P. tremuloides								1.0	
Prunus serotina	3	3	74	6.0	4.1	0.9	3.7	3.5	13.0
Quercus alba	6	7	980	12.0	9.6	11.7	11.1	3.5	38.8
Q. ellipsoidalis								1.0	
Q. macrocarpa								1.0	
Q. borealis	13	18	4540	26.0	24.7	54.3	35.0	5.5	192.5
Q. velutina								2.5	
Tilia americana	3	5	314	6.0	6.8	3.8	5.5	7.5	41.2
Ulmus americana	3	5	570	6.0	6.8	6.8	6.5	7.5	48.8
Ulmus rubra								8.0	
Carya cordiformis.	4	6	112	8.0	8.2	1.3	5.8	8.5	49.3
TOTALS	50	73	8367						674.7

Sauk County

Site 27 T12N, R7E, Sec 25
Private land

Tree No.	Basal Area, in.^{2}
261	460
262	280
263	300
264	190
265	190
266	250
267	350
268	180
269	270
270	380


Breezy Hill Road
To Wis. 33
owner's house
N
small parking area
Wall St.
1
2
3
4
5
6
7
8
9
10
hill
Sauk Co.
Columbia Co.
To Wis. 33
Wis Co. T
County W

TREE DATA SUMMARY SHEET

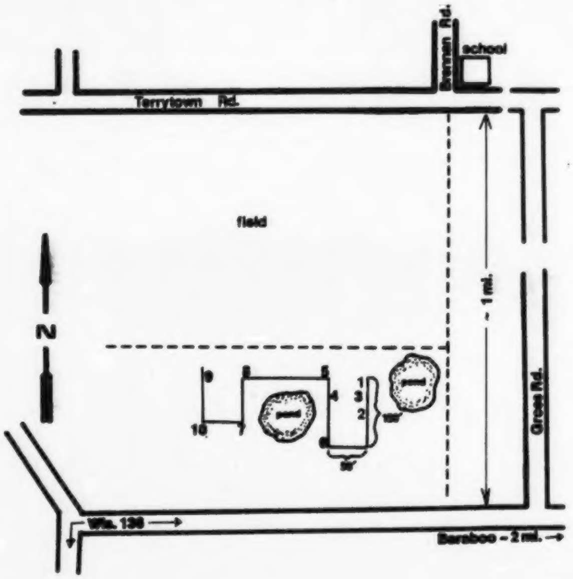
Site 28 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum	15	31	2771	31.2	44.3	29.7	35.1	10.0	351.0
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.	2	3	160	4.2	4.3	1.7	3.4	4.5	15.3
P. tremuloides								1.0	
Prunus serotina	6	6	780	12.5	8.6	8.4	9.8	3.5	34.3
Quercus alba	9	10	2065	18.8	14.3	22.2	21.7	3.5	76.0
Q. ellipsoidalis								1.0	
Q. macrocarpa	1	1	25	2.1	1.4	0.3	1.3	1.0	1.3
Q. borealis								5.5	
Q. velutina	11	14	3255	22.9	20.0	34.9	25.9	2.5	64.8
Tilia americana								7.5	
Ulmus americana	3	4	157	6.2	5.7	1.7	4.5	7.5	33.8
Ulmus rubra								8.0	
Robinia pseudoacacia	1	1	105	2.1	1.4	1.1	1.5	1.0	1.5
TOTALS	48	70	9318						578

Sauk County

Site 28 T12N, R6E, Sec 29
Private land

Tree No	Basal Area, in.^{2}
271	120
272	280
273	230
274	470
275	180
276	250
277	130
278	195
279	160
280	360


Brennan Rd.
school
Terrytown Rd.
field
N
1 mi.
Gross Rd.
9
8
5
1
4
3
2
10
7
6
100'
50'
Wis. 136
Baraboo – 2 mi.

TREE DATA SUMMARY SHEET

Site 29 Private land
20 sample plots

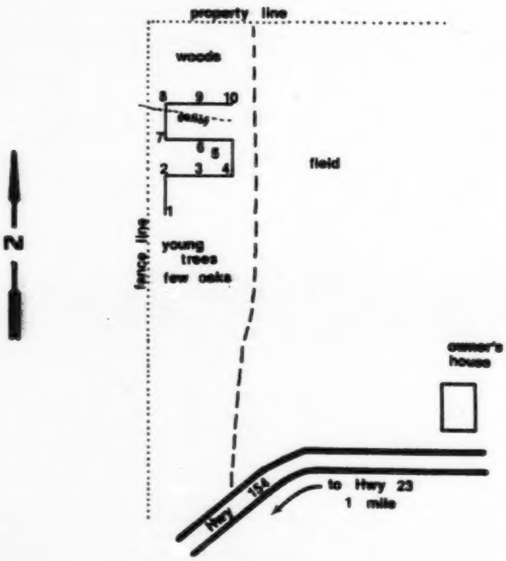
	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V	CI
Acer negundo								1.0	
Acer rubrum	7	13	840	13.2	19.1	11.8	14.7	7.0	102.9
Acer saccharum	1	1	290	1.9	1.5	4.1	2.5	10.0	25.0
Carya ovata	11	11	588	20,8	16.2	8.3	15.1	4.5	69.0
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana	2	2	26	3.8	2.9	0.4	2.4	8.5	27.9
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina	4	4	275	7.6	5.9	3.9	5.8	3.5	20.3
Quercus alba	7	7	1005	;3.2	10.3	14.1	12.5	3.5	43.8
Q. ellipsoidalis								1.0	
Q. macrocarpa	1	1	420	1.9	1.5	5.9	3.1	1.0	1.0
Q. borealis								5.5	
Q. velutina	10	14	3315	18.9	20.6	46.6	28.7	2.5	71.8
Tilia americana	2	2	200	3.8	2.9	1.4	2.7	7.5	20.2
Ulmus americana	8	13	349	15.1	19.1	4.9	13.0	7.5	97.5
Ulmus rubra								8.0	
TOTALS	53	68	7120						478.2

Sauk County

Site 29 T12N, R4E, Sec 27

Private land

Tree No.	Basal Area, in.^{2}
291	145
292	420
293	490
294	460
295	440
296	520
297	205
298	145
299	370
300	155


N
property line
woods
8
9
10
7
6
5
2
3
4
1
field
fence line
young trees few oaks
owner's house
Hwy 154
to Hwy 23 1 mile

TREE DATA SUMMARY SHEET

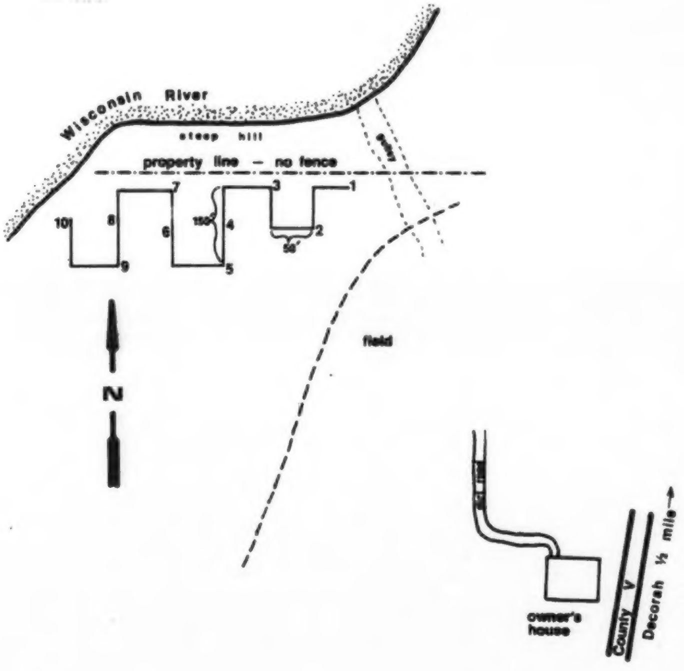
Site 30 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum	10	14	838	19.2	20.3	11.7	17.1	10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana	3	7	198	5.8	10.1	2.8	6.2	8.5	52.7
Populus granki.								4.5	
P. tremuloides								1.0	
Prunus serotina	6	7	660	11.5	10.1	9.2	10.3	3.5	36.0
Quercus alba	10	10	1255	11.2	14.5	17.5	17.1	3.5	59.8
Q. ellipsoidalis								1.0	
Q. Macrocarpa								1.0	
Q. borealis	11	18	2710	21.2	26.1	37.8	28.4	5.5	156.2
Q. velutina								2.5	
Tilia americana	2	2	150	3.8	2.9	2.1	2.9	7.5	21.8
Ulmus americana	2	2	95	3.8	2.9	1.3	2.7	7.5	20.2
Ulmus rubra								8.0	
Pinus resinosa	7	8	1020	13.5	11.6	14.2	13.1	3.0	39.3
Betula papyrifera	1	1	250	1.9	1.4	3.5	2.3	5.0	11.5
TOTALS	52	69	7176						568.5

Columbia County

Site 30 T11N, R9E, S ½, Sec 5
Private land

Tree No.	Basal Area, in.^{2}
281	140
282	160
283	220
284	115
285	230
286	250
287	260
288	170 double tree
289	200
290	240


Wisconsin River
steep hill
property line – no fence
1
2
3
4
5
6
7
8
9
10
150'
50'
N
field
owner's house
County V
Decorah ½ mile

TREE DATA SUMMARY SHEET

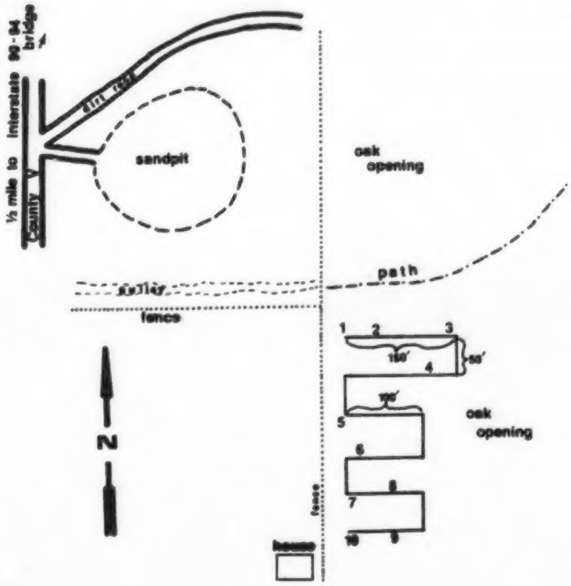
Site 31 Private land
20 sample plots

	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina								3.5	
Quercus alba								3.5	
Q. ellipsoidalis	18	45	4800	94.7	97.8	96.0	96.2	1.0	96.2
Q. macrocarpa	1	1	200	5.3	2.2	4.0	3.8	1.0	3.8
Q. borealis								5.5	
Q. velutina								2.5	
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	19	46	5000						100.0

Columbia County

Site 31 T11N, R8E, Sec 13
Public land

Tree No.	Basal Area, in.²
301	140
302	190
303	195
304	350
305	195
306	100 double tree
307	135 triple tree
308	150
309	250
310	135


90-94 bridge
½ mile to Interstate
County V
dirt road
sandpit
oak opening
path
gulley
fence
N
1
2
3
150'
50'
4
100'
5
oak opening
6
8
7
fence
house
10
9

TREE DATA SUMMARY SHEET

Site 32 Private land
20 sample plots

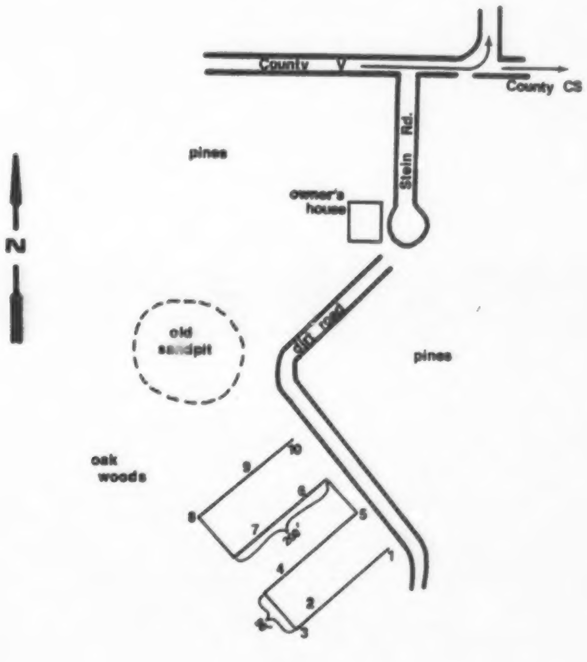
	No. Pts.	No. Trees	BA	% F	% D	% Do	I.V.	C.A.V.	CI
Acer negundo								1.0	
Acer rubrum								7.0	
Acer saccharum								10.0	
Carya ovata								4.5	
Fraxinus amer.								6.5	
Juglans cinerea								7.5	
Morus rubra								3.5	
Ostrya virginiana								8.5	
Populus grandi.								4.5	
P. tremuloides								1.0	
Prunus serotina	1	1	45	4.0	1.6	0.6	2.1	3.5	7.4
Quercus alba	4	4	190	16.0	6.4	2.8	8.4	3.5	29.4
Q. ellipsoidalis								1.0	1.0
Q. macrocarpa	1	1	110	4.0	1.6	1.6	2.4	1.0	2.4
Q. borealis								5.5	5.5
Q. velutina	19	57	6551	76.0	90.5	95.0	87.2	2.5	218
Tilia americana								7.5	
Ulmus americana								7.5	
Ulmus rubra								8.0	
TOTALS	25	63	6896						257.2

Columbia County

Site 32 T11N, R8E, Sec 33

Private land

Tree No.	Basal Area, in.^{2}
311	190
312	205
313	140
314	240 double tree
315	170
316	110
317	105
318	120
319	200
320	110


County V
County CS
Stein Rd.
pines
owner's house
N
old sandpit
dirt road
pines
oak woods
10
9
6
8
7
5
1
4
2
3

APPENDIX D

NUMBER OF QUADRATS AT SAMPLING SITES CONTAINING EACH LICHEN SPECIES

Species number[b]	Site 1[a] Northeast aspect 1974	Site 1[a] Northeast aspect 1978	Site 1[a] Northwest aspect 1974	Site 1[a] Northwest aspect 1978
1	7	8.9[c]	7	7.8[c]
2	1	2.2	3	3.3
3	0	2.2	0	2.2
4	0	0	0	1.1
5	0	0	0	1.1
7	0	0	0	2.2
8	3	7.8	4	8.9
11	0	0	1	0
14	1	0	1	0
15	1	2.2	0	1.1
16	3	2.2	1	2.2
17	0	1.1	0	0
18	1	0	0	0
20	2	1.1	1	1.1
21	5	1.1	3	0
22	0	2.2	2	0
23	8	2.2	6	3.3
24	0	1.1	0	3.3
25	2	1.1	2	1.1
26	2	2.2	3	4.4
29	0	0	0	1.1
30	4	2.2	3	1.1
33	1	0	0	0
35	10	10	9	10
36	3	0	3	3.3
38	1	0	1	2.2
39	1	1.1	2	3.3
40	0	0	0	2.2
42	1	0	2	1.1
46	0	2.2	3	3.3
Number of species	19	18	19	23

Species number[b]	Site 2 Northeast aspect 1974	Site 2 Northeast aspect 1978	Site 2 Northwest aspect 1974	Site 2 Northwest aspect 1978
1	10	8	10	8
2	3	0	4	1
3	2	0	6	1
5	0	1	1	1
7	0	1	0	0
8	5	4	2	4
9	0	0	0	1
12	1	1	5	2
14	0	1	0	0
15	0	2	0	1
16	4	5	5	6
19	2	1	1	2
20	4	1	2	1
21	4	3	7	3
22	0	0	0	2
23	4	5	2	4
25	2	0	1	0
26	9	8	8	6
28	1	0	0	0
30	1	3	0	1
32	1	1	2	3
33	2	0	0	0
35	10	8	8	10
36	0	1	4	2
37	0	0	0	1
38	0	0	2	0
39	0	2	1	3
41	0	0	1	0
42	0	1	0	0
46	6	4	6	7
	18	20	20	22

Species number	Site 3 Northeast aspect 1974	Site 3 Northeast aspect 1978	Site 3 Northwest aspect 1974	Site 3 Northwest aspect 1978
1	7	6	10	5
2	3	1	4	2
3	0	1	2	1
5	0	1	0	1
8	0	5	0	8
12	4	2	2	5
13	0	1	0	0
14	1	0	1	0
15	0	1	0	0
16	6	4	6	7
18	2	1	3	0
19	1	0	1	0
20	2	5	2	4
21	2	1	1	1
22	0	1	0	1
23	2	2	2	2
24	0	1	0	0
25	1	1	0	0
26	9	8	6	5
27	0	1	0	0
28	2	0	0	0
30	0	1	0	0
32	1	2	0	2
35	10	10	10	8
36	0	0	0	1
39	5	4	2	2
41	0	0	1	0
44	0	1	0	0
46	3	3	5	4
Number of species	17	24	16	17

Species number	Site 4 Northeast aspect 1974	Site 4 Northeast aspect 1978	Site 4 Northwest aspect 1974	Site 4 Northwest aspect 1978
1	6	3	8	5
2	1	0	4	0
3	4	2	2	0
5	0	1	0	0
8	2	4	1	4
12	3	6	6	3
14	0	0	2	0
16	4	5	4	6
18	2	1	1	0
19	0	1	0	0
20	3	4	6	4
21	1	2	2	3
23	1	1	0	1
26	0	0	1	3
32	1	0	0	0
35	7	9	10	10
36	0	4	1	3
38	1	1	1	2
41	0	0	0	1
42	1	0	0	0
43	0	0	0	1
46	4	4	5	7
	15	15	15	14

---

[a] See Figure 7 for locations of sites.
[b] See Table 20 for names of species.
[c] Since only nine trees suitable for sampling were found in 1978 at site 1, occurrence values were divided by 10.9 so that they are equivalent to values at other sites.

	Site 5			
	Northeast aspect		Northwest aspect	
Species number	1974	1978	1974	1978
1	8	6	5	7
2	0	0	1	1
3	0	0	1	3
7	0	1	0	0
8	0	1	0	4
12	4	4	1	3
16	3	2	0	3
18	0	0	1	0
20	0	4	2	6
21	4	2	3	1
26	1	0	3	2
32	1	0	1	2
35	10	9	8	9
36	0	1	0	1
38	1	1	2	1
39	0	0	0	2
42	1	0	0	0
46	6	6	4	8
Number of species	10	11	12	15

	Site 7			
	Northeast aspect		West aspect	
Species number	1974	1978	1974	1978
1	7	5	3	7
2	0	0	1	0
4	0	0	0	1
6	0	1	0	1
7	1	3	6	6
8	2	4	2	3
9	0	0	0	1
15	2	7	0	3
17	0	1	0	0
20	0	3	2	4
21	0	0	0	1
22	1	1	1	1
23	5	0	3	1
24	0	2	1	6
25	0	0	1	0
26	0	1	0	0
29	0	1	0	0
30	5	1	0	3
35	10	10	10	9
36	1	2	4	1
38	2	0	1	0
39	2	2	3	4
40	0	0	0	2
46	2	0	4	1
48	0	0	0	1
	12	15	11	19

	Site 8			
	Northeast aspect		West aspect	
Species number	1974	1978	1974	1978
1	8	6	6	6
2	0	0	0	1
3	1	1	2	0
4	0	0	0	1
5	1	0	0	0
7	0	0	0	1
8	2	3	3	5
9	0	0	0	1
12	0	2	1	1
14	1	2	1	2
16	5	7	5	5
17	3	0	0	0
18	1	2	0	0
19	0	0	1	0
20	4	1	3	2
21	3	2	1	0
22	1	2	0	0
23	4	1	3	3
24	0	0	0	1
26	1	4	0	3
31	0	0	3	0
32	0	2	3	2
35	8	7	10	9
36	1	1	3	2
38	3	0	1	0
39	0	0	1	1
42	0	1	0	0
44	0	1	0	0
46	4	2	3	5
Number of species	17	18	17	18

	Site 9			
	Northeast aspect		West aspect	
Species number	1974	1978	1974	1978
1	5	1	7	4
2	0	1	0	1
3	0	1	0	1
8	0	4	3	5
11	1	0	0	0
12	1	0	0	1
14	0	1	0	0
15	0	1	0	3
16	1	3	2	0
18	3	0	2	1
19	0	1	0	0
20	1	7	7	6
21	1	3	1	4
22	0	3	2	2
23	8	7	5	7
24	0	1	0	0
25	1	0	1	1
26	2	1	1	4
28	0	0	1	0
30	3	2	2	1
32	1	0	1	0
35	9	10	10	9
36	0	0	1	2
38	1	0	1	0
39	2	0	1	0
42	2	2	2	1
43	0	0	0	1
44	0	1	0	0
46	0	1	2	3
47	1	0	0	0
	17	19	19	18

	Site 10			
Species number	Northeast aspect 1974	Northeast aspect 1978	West aspect 1974	West aspect 1978
1	6	3	3	0
2	2	1	0	0
3	0	2	1	2
7	0	0	0	1
8	5	5	2	1
12	4	6	6	2
14	2	0	0	0
16	3	1	0	0
18	0	1	0	0
20	8	7	5	5
21	0	2	0	0
22	1	0	0	0
23	0	0	0	1
26	2	0	2	0
32	2	1	0	0
35	10	10	6	7
36	4	3	6	3
38	3	3	2	1
39	2	2	1	2
41	1	0	0	0
42	2	2	0	1
46	3	5	5	4
Number of species	17	16	11	12

	Site 11			
Species number	Northeast aspect 1974	Northeast aspect 1978	West aspect 1974	West aspect 1978
1	8	8	3	1
2	2	1	0	0
3	0	1	0	3
4	0	0	0	1
7	0	1	0	3
8	0	1	1	1
9	0	1	0	1
12	4	2	1	3
15	0	1	0	0
16	1	2	0	1
20	5	3	8	3
21	2	0	0	0
22	0	0	1	0
26	3	3	0	1
32	1	0	0	0
35	9	7	8	7
39	1	3	1	2
40	0	0	0	2
42	1	0	0	1
46	1	4	7	5
	12	14	8	15

	Site 12			
Species number	Northeast aspect 1974	Northeast aspect 1978	West aspect 1974	West aspect 1978
1	2	1	1	3
2	0	0	0	1
3	2	0	0	1
7	0	1	0	0
8	0	1	0	0
12	8	4	6	8
15	0	0	0	1
16	0	0	0	1
18	0	0	1	0
20	2	1	3	2
26	0	1	0	0
35	8	9	7	7
36	0	0	1	0
39	0	1	0	0
42	1	0	0	1
46	2	5	3	2
Number of species	7	9	7	10

	Site 13			
Species number	Northeast aspect 1974	Northeast aspect 1978	Southwest aspect 1974	Southwest aspect 1978
1	6	9	5	4
2	0	6	0	0
3	0	5	0	1
4	1	2	1	0
5	0	1	0	0
6	0	0	0	1
7	0	0	1	2
8	3	4	2	6
9	1	1	9	5
14	4	2	2	0
15	0	2	1	0
16	5	3	0	1
17	1	0	0	0
18	1	0	0	0
20	5	8	5	6
22	3	4	3	1
23	4	2	5	4
24	0	5	0	2
25	2	0	0	0
26	4	7	5	6
30	1	2	0	0
31	1	0	0	0
32	7	5	1	2
35	10	9	10	10
36	0	0	2	0
38	2	0	0	0
39	1	2	4	2
40	0	0	0	1
42	0	1	0	0
45	0	1	0	0
46	1	5	8	7
48	0	0	0	1
	20	22	16	18

	Site 14			
	Northeast aspect		Southwest aspect	
Species number	1974	1978	1974	1978
1	10	9	8	10
2	0	4	0	2
4	0	2	0	0
5	1	0	0	0
7	0	0	0	1
8	0	5	4	3
9	0	0	4	0
14	1	0	0	0
15	0	1	0	2
17	1	2	0	0
20	0	2	2	2
21	2	1	2	3
22	0	1	0	2
23	0	4	0	1
24	3	2	2	4
26	0	2	1	1
30	4	7	3	3
31	2	0	4	0
32	1	0	1	0
35	10	10	10	10
36	1	0	1	1
38	0	1	2	0
39	3	3	1	4
42	1	1	1	0
Number of species	13	17	15	15

	Site 15			
	Northeast aspect		Southwest aspect	
Species number	1974	1978	1974	1978
1	6	8	6	6
2	0	1	0	1
3	1	1	0	0
7	0	2	0	0
8	5	5	5	4
9	0	1	0	0
12	1	0	0	0
16	0	2	0	0
18	3	1	1	0
19	2	0	0	0
20	5	2	3	2
21	5	7	2	4
22	2	1	2	1
23	0	1	1	0
25	0	0	1	0
26	4	3	2	1
30	0	1	0	0
31	0	1	1	1
35	10	10	10	10
36	0	0	2	2
38	1	1	0	0
39	2	1	6	4
41	0	0	0	1
42	1	0	0	0
46	2	3	7	6
	15	19	14	13

	Site 16			
	Northeast aspect		Southwest aspect	
Species number	1974	1978	1974	1978
1	9	6	4	4
2	1	0	0	0
4	0	0	0	1
7	0	0	1	0
8	4	3	5	4
9	4	0	5	3
11	1	0	0	0
12	1	1	0	0
14	0	1	0	1
16	6	6	3	0
20	5	7	6	6
22	5	7	5	1
23	3	5	2	2
24	0	1	0	0
26	7	8	3	6
30	0	1	0	0
31	1	0	0	1
32	1	0	0	0
35	10	8	10	9
38	0	0	1	0
39	6	3	3	4
41	0	0	1	0
42	1	0	0	0
44	1	0	0	0
46	7	5	9	9
48	0	1	0	0
Number of species	18	15	14	13

	Site 17			
	Northeast aspect		Southwest aspect	
Species number	1974	1978	1974	1978
1	8	4	5	7
2	0	0	0	8
8	5	8	5	8
9	5	1	5	1
14	0	1	0	1
15	0	0	0	5
16	0	1	0	1
20	1	6	3	5
21	0	2	1	0
22	5	5	3	7
23	2	4	2	2
24	0	1	0	0
25	1	1	0	0
26	3	4	4	7
30	2	1	1	4
31	9	8	7	10
32	0	1	1	1
33	0	1	0	0
35	10	10	10	10
36	0	1	0	0
39	0	4	3	3
40	0	1	0	0
46	1	7	4	3
	12	21	14	17

Species number	Site 19 Northeast aspect 1974	Site 19 Northeast aspect 1978	Site 19 South-southeast aspect 1974	Site 19 South-southeast aspect 1978
1	8	6	5	8
2	1	0	0	0
3	0	1	0	0
4	1	1	0	0
7	1	1	0	2
8	6	6	7	7
14	0	0	1	0
15	6	8	2	2
17	0	0	0	1
18	0	0	1	1
20	5	5	6	9
21	1	1	0	0
23	0	4	2	4
25	0	0	0	1
26	0	1	0	0
30	1	2	0	1
31	0	0	1	0
32	1	0	0	0
35	10	10	10	10
36	1	2	1	3
38	0	0	1	1
40	0	0	0	1
42	1	0	0	0
46	0	0	0	1
Number of species	13	13	11	15

Species number	Site 20 Northeast aspect 1974	Site 20 Northeast aspect 1978	Site 20 South-southeast aspect 1974	Site 20 South-southeast aspect 1978
1	6	4	4	6
2	0	4	1	0
3	1	0	0	0
4	1	0	0	1
6	1	0	0	0
7	0	2	0	5
8	9	8	9	10
9	0	0	3	1
11	0	1	0	0
14	2	2	1	1
15	0	3	0	2
16	4	1	1	0
17	1	3	1	1
20	6	8	9	7
21	0	2	1	3
22	1	1	0	1
23	7	7	6	8
24	0	1	0	2
25	0	1	0	0
26	3	4	3	4
28	1	0	0	0
30	5	3	2	3
31	0	4	2	2
32	0	0	1	0
35	10	10	9	10
36	0	3	2	2
38	2	1	2	0
39	2	0	2	3
40	0	1	0	1
42	0	1	0	0
46	0	3	5	6
	17	24	19	20

Species number	Site 21 Northeast aspect 1974	Site 21 Northeast aspect 1978	Site 21 South-southeast aspect 1974	Site 21 South-southeast aspect 1978
1	6	6	7	8
2	1	1	1	5
3	0	1	0	0
4	0	1	0	2
8	4	10	7	7
14	1	0	0	0
15	0	0	0	2
15	1	0	0	0
19	0	0	1	0
20	6	9	6	6
21	5	3	3	5
22	2	1	3	1
23	2	7	1	3
24	2	1	1	2
25	0	0	0	2
26	2	6	0	7
30	2	0	0	4
31	3	1	3	1
32	0	0	1	0
35	9	10	9	9
36	1	3	5	3
38	0	0	0	2
39	2	3	3	3
40	0	1	0	0
Number of species	16	16	14	18

Species number	Site 22 Northeast aspect 1974	Site 22 Northeast aspect 1978	Site 22 South-southeast aspect 1974	Site 22 South-southeast aspect 1978
1	7	5	5	2
2	2	4	2	1
3	1	2	0	1
4	2	1	0	0
5	0	1	0	1
7	1	5	0	1
8	7	1	6	9
9	1	0	0	0
12	4	1	0	0
14	2	2	0	1
15	0	1	0	0
16	8	7	4	4
18	2	5	4	4
19	4	0	2	0
20	7	6	6	2
21	5	2	4	5
22	1	1	2	0
23	3	1	5	4
24	0	0	0	2
25	0	5	0	0
26	6	6	0	7
30	4	3	0	0
31	4	0	0	0
32	1	2	0	0
35	10	10	10	10
36	5	3	5	9
38	7	2	3	1
39	3	1	4	1
42	2	3	1	0
44	1	0	0	0
45	1	0	0	0
46	3	1	6	8
	28	26	16	19

Species number	Site 23 Northeast aspect 1974	Site 23 Northeast aspect 1978	Site 23 South-southeast aspect 1974	Site 23 South-southeast aspect 1978
1	1	5	2	3
2	1	0	0	0
3	1	1	0	0
4	0	0	2	1
7	0	0	1	1
8	4	7	8	9
10	0	1	0	1
14	1	2	0	2
15	0	0	1	0
16	4	4	2	1
17	0	1	0	0
18	0	3	0	1
20	5	9	6	5
21	4	2	5	6
22	1	2	2	3
23	9	10	9	8
24	0	1	0	1
25	0	0	2	1
26	9	9	8	10
27	0	1	1	1
29	0	2	0	0
30	4	3	2	0
32	0	1	0	0
35	10	8	8	10
36	1	1	1	0
38	0	1	1	0
39	1	0	3	1
42	2	5	1	3
46	3	1	2	3
48	0	0	0	1
Number of species	17	23	20	21

Species number	Site 25 Northeast aspect 1974	Site 25 Northeast aspect 1978	Site 25 East aspect 1974	Site 25 East aspect 1978
1	7	7	5	7
2	0	5	0	1
7	0	0	1	0
8	6	10	10	9
9	0	0	1	1
12	0	2	0	1
14	3	1	2	2
15	2	3	1	0
16	3	5	2	2
18	1	0	1	0
20	5	6	8	7
21	0	4	1	2
22	2	3	3	5
23	6	7	3	8
24	0	0	1	0
26	3	4	3	4
27	0	1	0	0
30	2	1	1	0
31	0	0	2	0
35	10	10	10	10
36	2	2	0	3
38	1	0	1	1
39	2	1	3	4
40	0	0	0	1
42	0	1	0	1
44	0	1	0	0
46	2	2	6	5
	16	20	20	19

Species number	Site 26 Northeast aspect 1974	Site 26 Northeast aspect 1978	Site 26 East aspect 1974	Site 26 East aspect 1978
1	7	4	5	5
2	2	2	2	3
3	0	0	1	0
4	0	0	0	1
8	5	4	2	6
12	0	1	1	1
14	2	0	0	0
15	1	0	1	2
16	4	2	0	3
17	0	1	0	0
18	1	0	1	1
20	8	6	9	8
21	2	6	2	3
22	0	1	1	0
23	1	5	2	5
24	4	1	1	0
25	2	0	2	0
26	0	2	0	1
29	1	0	0	1
30	4	1	1	1
31	0	0	1	0
35	9	9	8	8
36	3	1	2	4
38	0	0	1	0
39	3	0	1	2
44	0	1	0	0
45	1	0	0	0
46	0	0	1	0
Number of species	18	16	20	17

Species number	Site 27 Northeast aspect 1974	Site 27 Northeast aspect 1978	Site 27 East aspect 1974	Site 27 East aspect 1978
1	2	4	1	0
2	7	7	6	1
3	0	0	1	0
4	0	1	0	0
7	7	5	3	5
8	7	8	7	7
12	2	5	2	5
16	2	0	0	1
18	1	0	0	0
20	6	6	6	8
21	5	6	5	4
22	1	1	2	0
25	1	2	0	0
26	1	2	0	2
34	0	0	0	1
35	5	9	10	10
36	8	10	7	6
38	5	1	4	1
39	1	1	1	1
40	0	0	0	2
42	0	3	1	0
44	0	1	0	0
46	5	6	6	5
48	0	0	0	1
	17	18	15	16

	Site 28			
	Northeast aspect		East aspect	
Species number	1974	1978	1974	1978
1	2	3	0	2
2	4	1	3	0
3	4	1	2	0
4	1	1	2	0
5	0	3	0	1
7	2	2	1	1
8	4	6	5	7
9	0	0	1	0
12	4	7	4	7
14	2	0	1	1
15	1	0	0	0
16	4	0	4	2
18	1	0	3	2
19	1	0	1	0
20	8	8	10	7
21	4	7	4	4
23	3	1	1	0
26	2	1	1	2
32	1	1	2	0
35	9	9	8	10
36	6	6	9	4
38	5	1	2	0
39	0	1	0	0
42	2	1	0	2
44	1	0	1	0
46	5	4	7	7
48	1	1	0	0
Number of species	24	20	21	15

	Site 29			
	Northeast aspect		East aspect	
Species number	1974	1978	1974	1978
1	0	5	0	2
2	6	0	2	0
3	1	1	0	3
7	0	0	2	2
8	0	3	4	4
12	7	8	10	8
14	0	1	0	0
16	1	2	1	1
18	0	1	1	1
20	5	5	4	6
21	4	4	4	6
25	0	1	0	1
26	0	3	0	1
32	1	0	0	2
35	7	7	4	6
36	3	4	5	4
38	1	1	1	1
39	1	0	1	0
42	3	7	2	6
46	4	6	4	6
Number of species	13	16	14	17

	Site 30	
	Northeast aspect	
Species number	1974	1978
1	9	6
2	4	9
3	1	0
8	0	2
12	7	10
14	2	0
16	1	0
18	4	0
20	4	5
21	6	3
22	1	1
23	1	1
24	0	1
25	1	2
26	0	5
35	9	8
36	6	1
38	1	1
39	1	0
42	1	5
46	1	0
Number of species	18	15

	Site 31	
	Northeast aspect	
Species number	1974	1978
1	5	6
2	1	4
3	0	3
5	0	1
7	1	3
8	7	10
9	2	3
14	0	1
15	0	1
16	3	4
17	1	1
18	1	0
20	9	9
22	1	4
23	7	8
24	0	1
26	9	9
30	1	2
32	2	2
33	0	1
35	10	10
36	1	3
37	0	1
38	0	1
39	6	5
42	0	4
46	8	8
48	0	3
Number of species	18	27

	Site 32	
	Northeast aspect	
Species number	1974	1978
1	2	8
2	3	0
3	3	0
4	1	1
7	1	0
8	5	4
14	2	1
15	0	1
16	4	5
17	1	0
18	1	0
20	6	3
21	2	1
22	1	2
23	6	9
24	0	1
26	5	2
28	1	0
29	2	3
30	3	5
31	0	2
32	2	2
35	9	9
36	3	3
38	2	1
39	1	4
Number of species	23	20

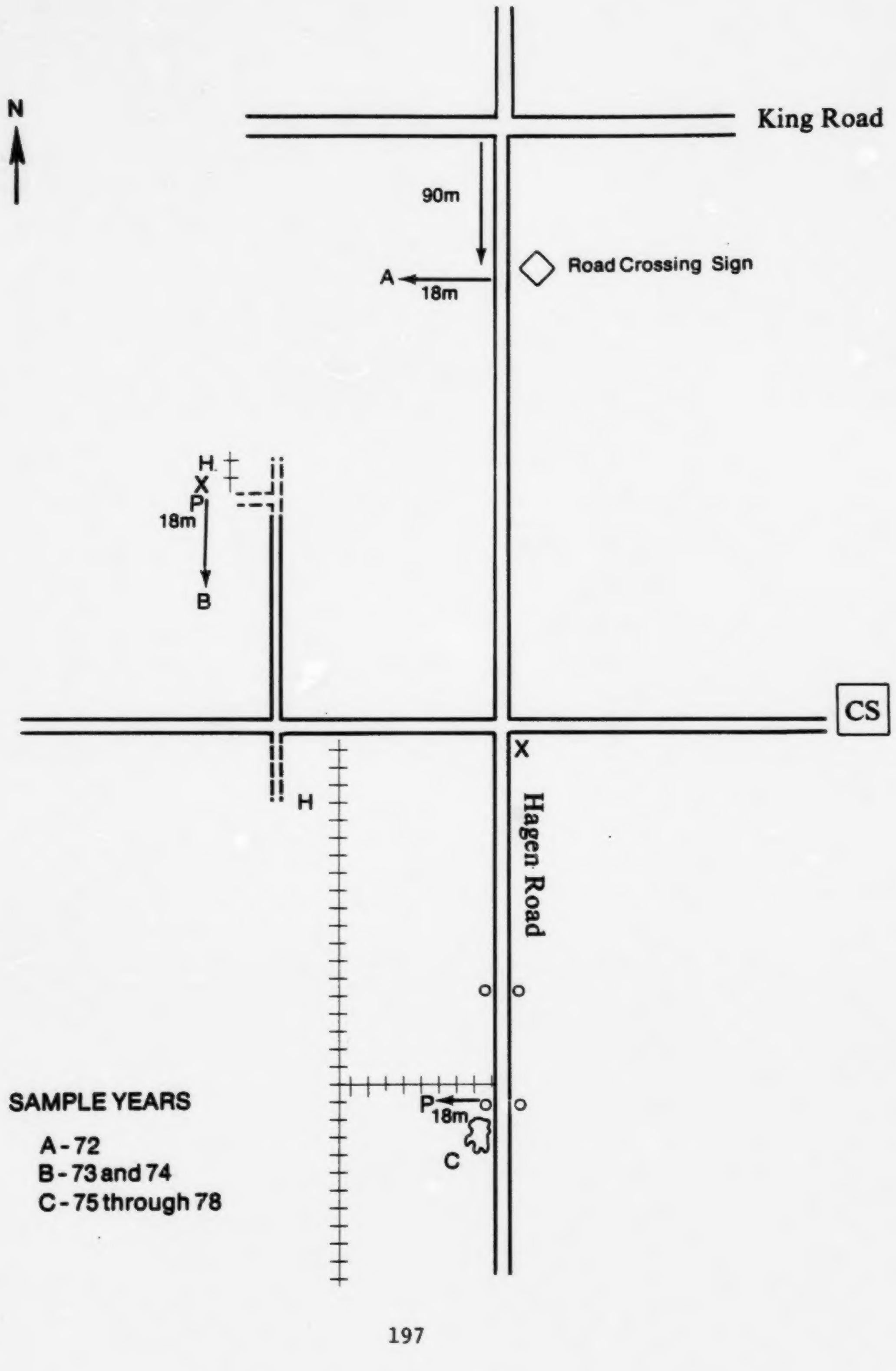
APPENDIX E

LOCATION OF ALFALFA FIELDS AND SAMPLING AREA AT EACH SITE

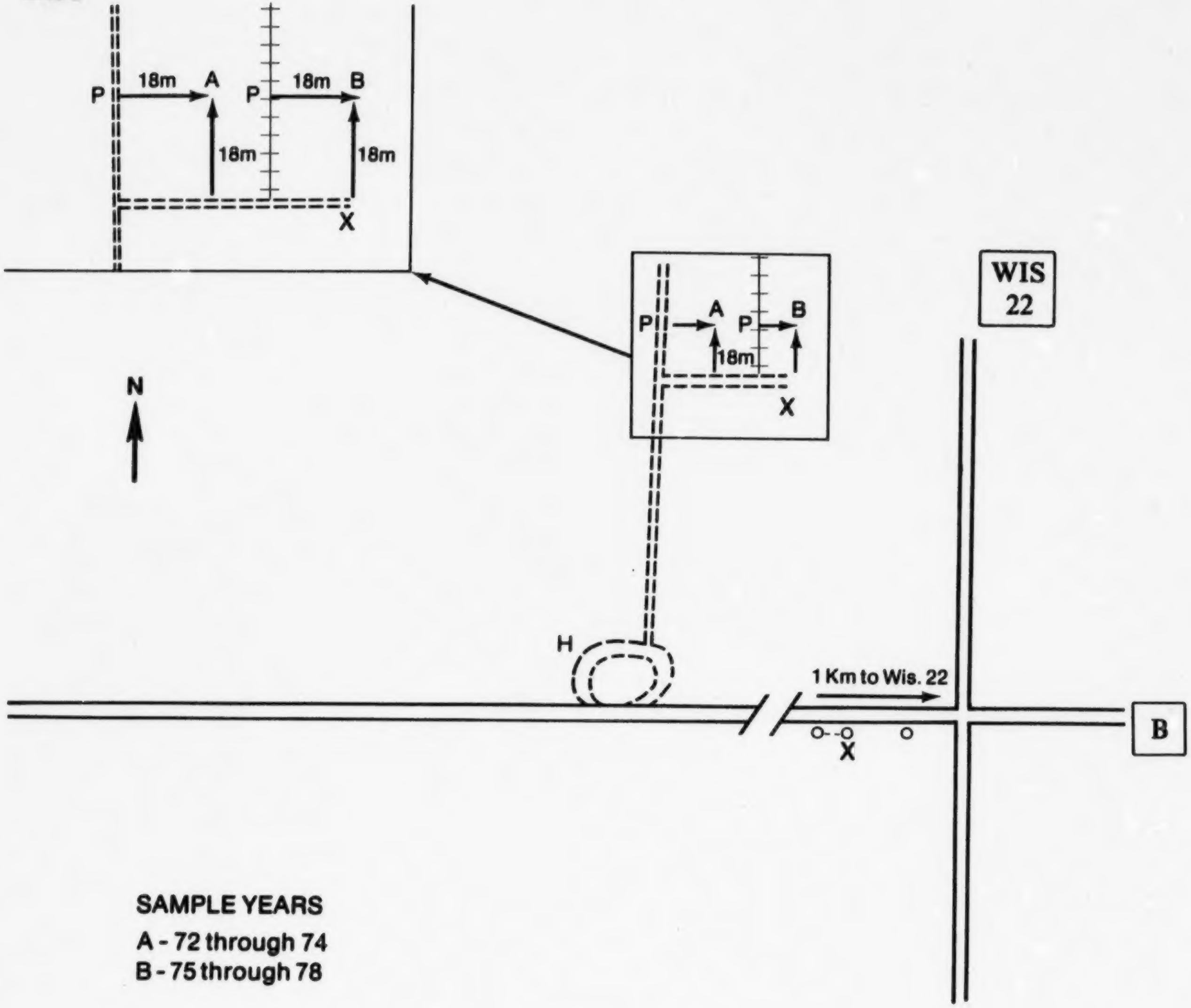
LEGEND

Gravel or Dirt Road	╌╌╌╌╌	Farmhouse	H
Paved Road	═══	Fence Line or Field Boundary	┼┼┼┼┼
Road Identification	☐	Roadside Guardpost	o
Road sign	◇	Electric Pole	⊖
Small Tree or Shrub	☁	Gate	o–o
Location of Giant Ragweed Stand	X	Blackberry	BB
Sampling Sites	A,B,C,D	Stream	≈
Point from which Site Photograph was taken	P		

Site 1

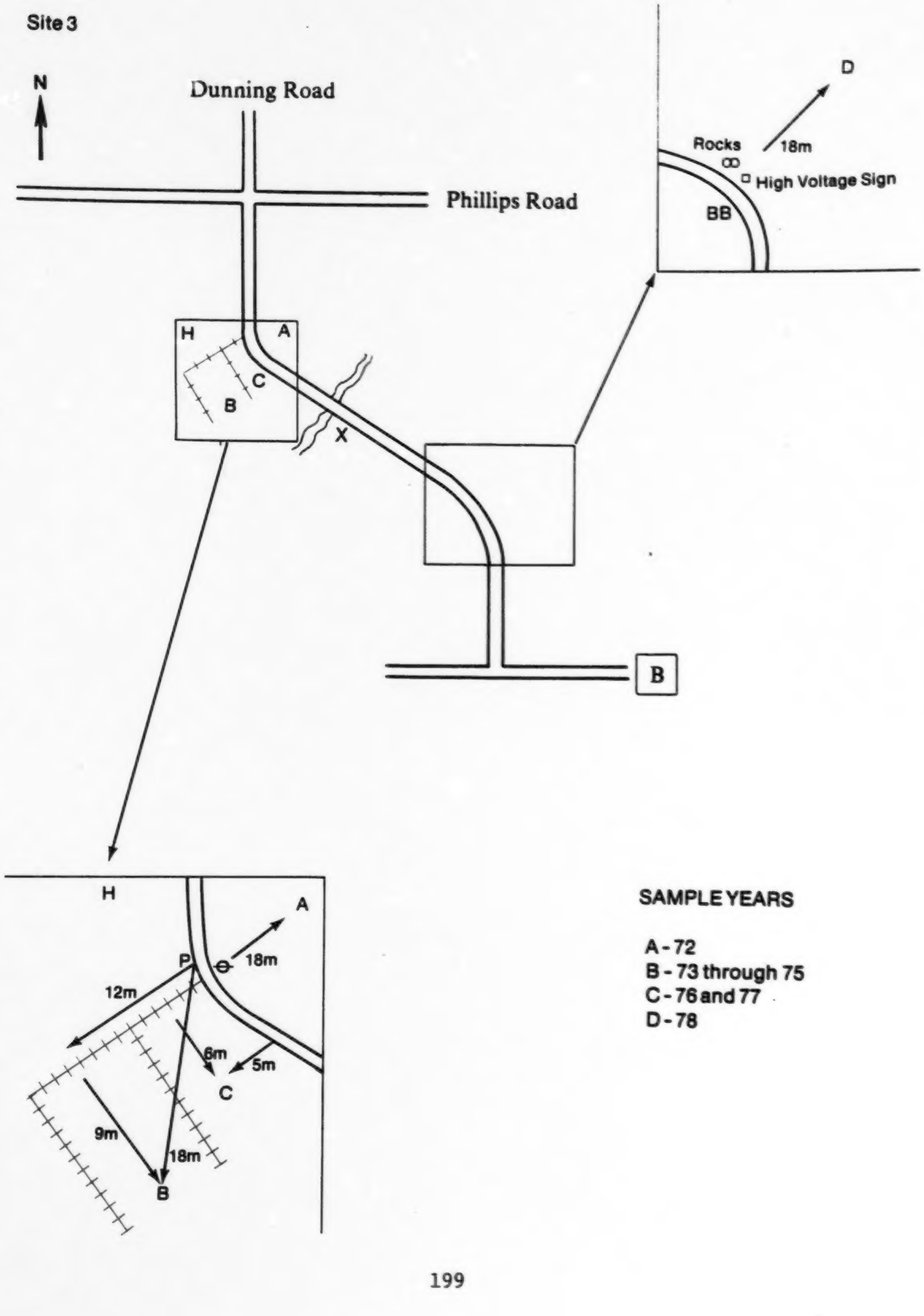

N
King Road
90m
A
18m
Road Crossing Sign
H
X
P
18m
B
CS
X
H
Hagen Road
P
18m
C
SAMPLE YEARS
A - 72
B - 73 and 74
C - 75 through 78

Site 2


P
18m
A
P
18m
B
18m
18m
X
P
A
P
B
18m
X
N
WIS 22
H
1 Km to Wis. 22
X
B

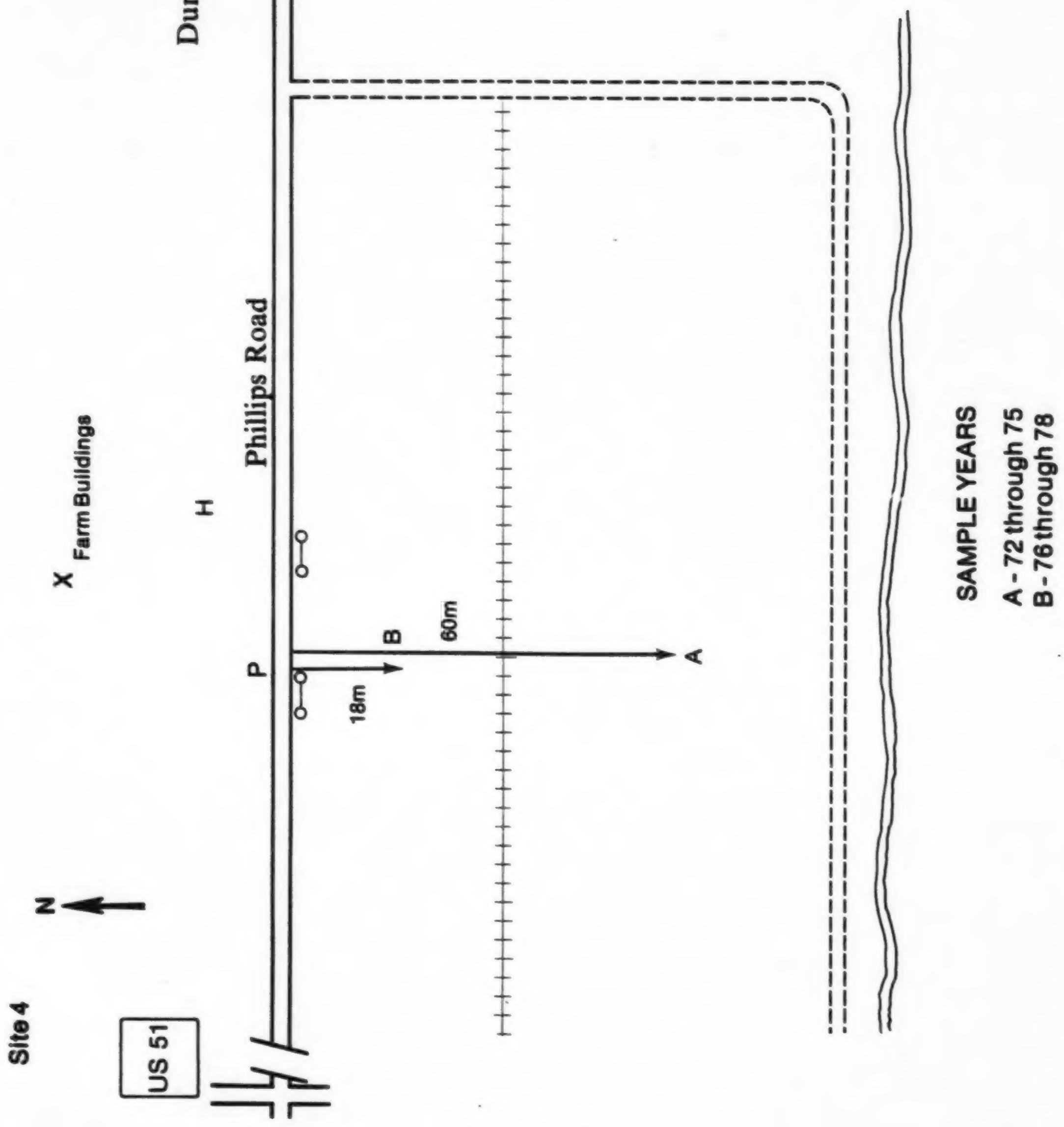
SAMPLE YEARS
A - 72 through 74
B - 75 through 78

Site 3

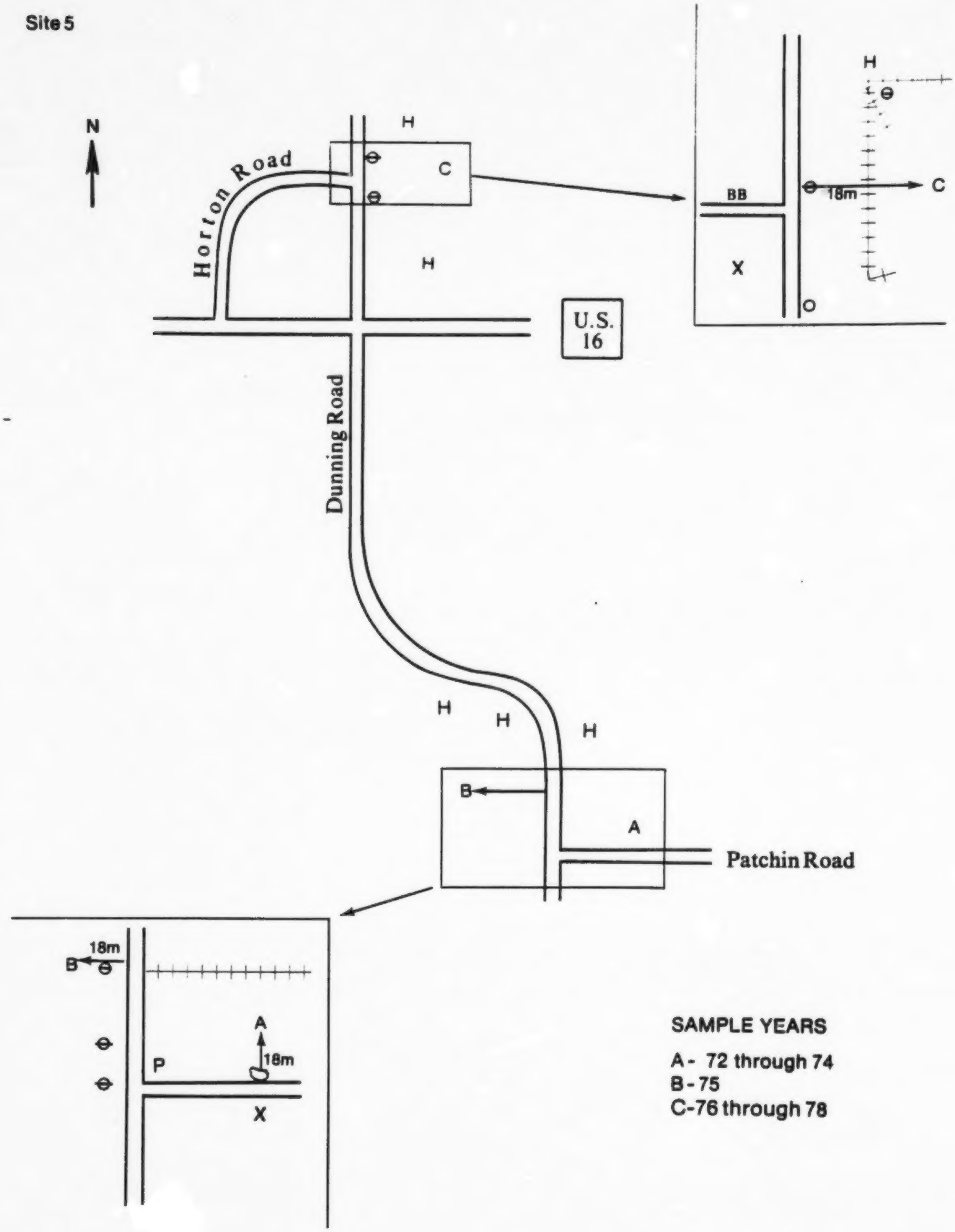

N
Dunning Road
Phillips Road
H
A
C
B
X
D
Rocks
18m
High Voltage Sign
BB
B
H
A
P
18m
12m
6m
5m
C
9m
18m
B

SAMPLE YEARS

A - 72
B - 73 through 75
C - 76 and 77
D - 78

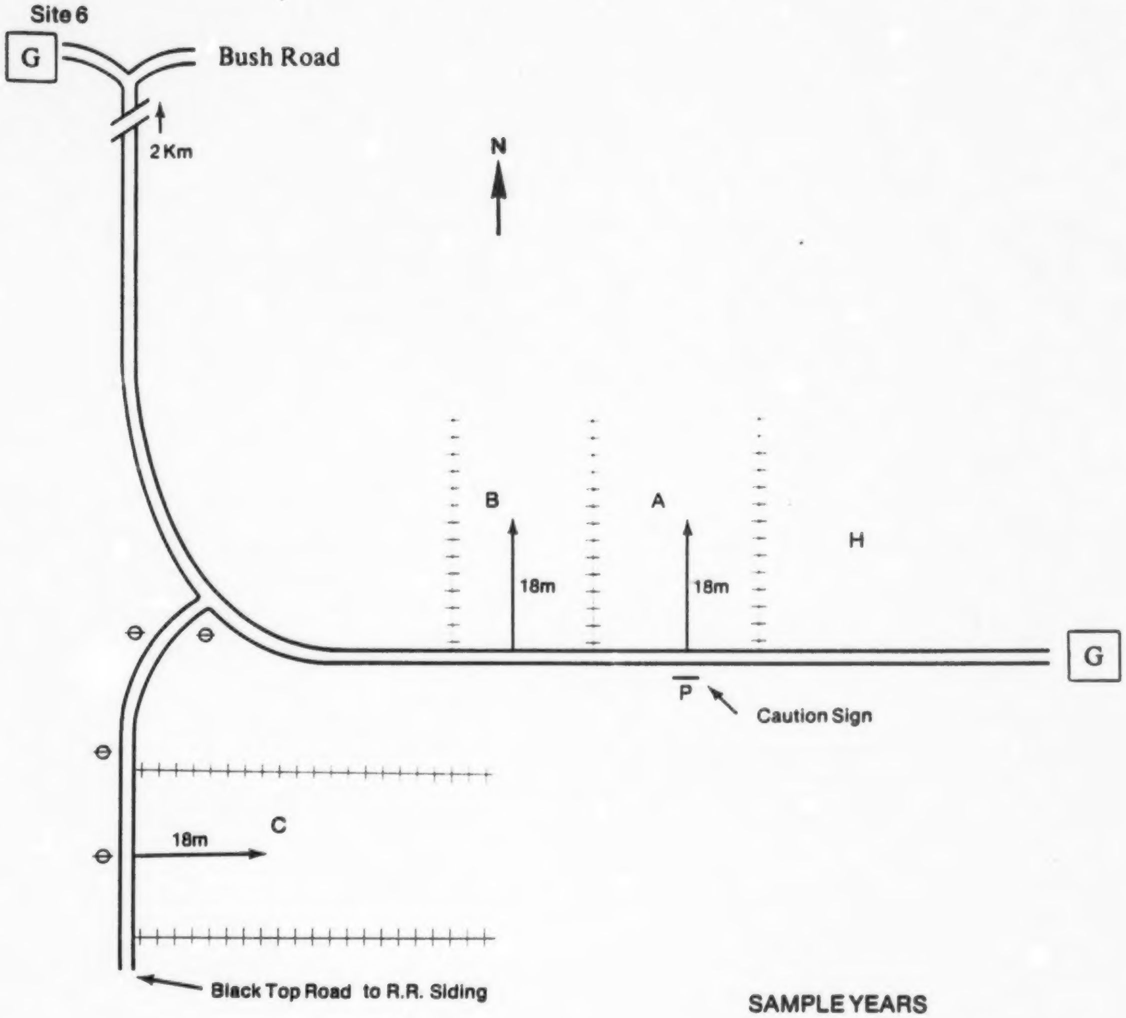

Site 4
US 51
N
X Farm Buildings
H
P
Phillips Road
Dunning Road
2 Km
18m
B
60m
A
SAMPLE YEARS
A - 72 through 75
B - 76 through 78

Site 5


N
Horton Road
H
C
H
U.S. 16
Dunning Road
H
H
H
B
A
Patchin Road
H
BB
18m
C
X
O
18m
B
A
18m
P
X

SAMPLE YEARS

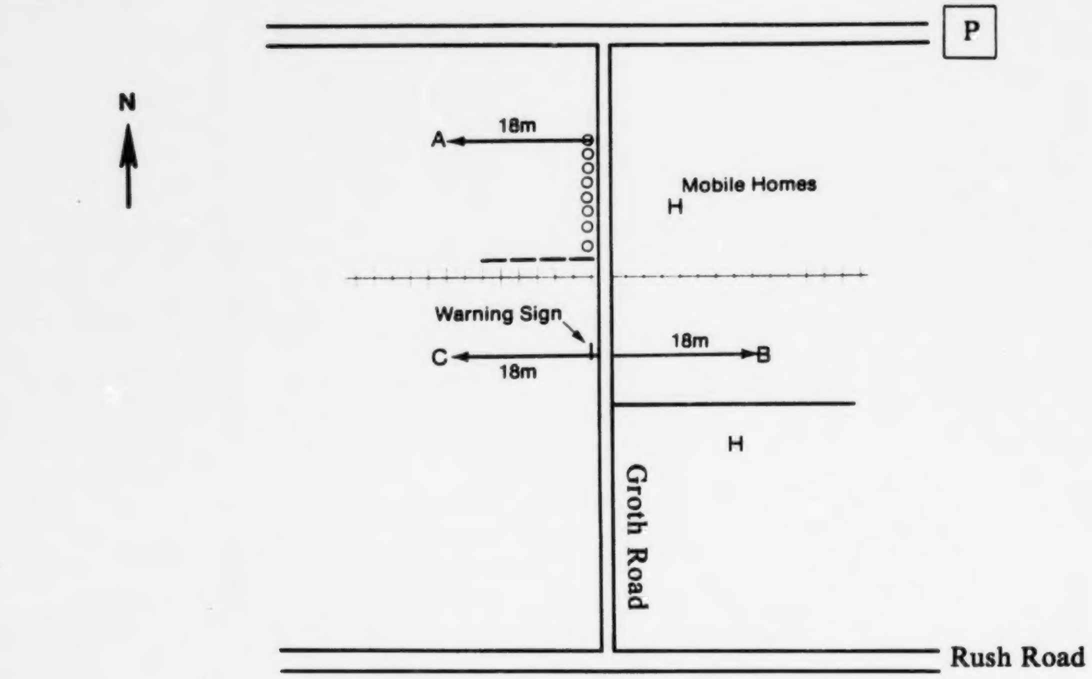
A - 72 through 74
B - 75
C - 76 through 78


Site 6
G
Bush Road
2 Km
N
B
A
H
18m
18m
G
P
Caution Sign
C
18m
Black Top Road to R.R. Siding

SAMPLE YEARS

A - 72 through 73, 75 through 77
B - 74
C - 78

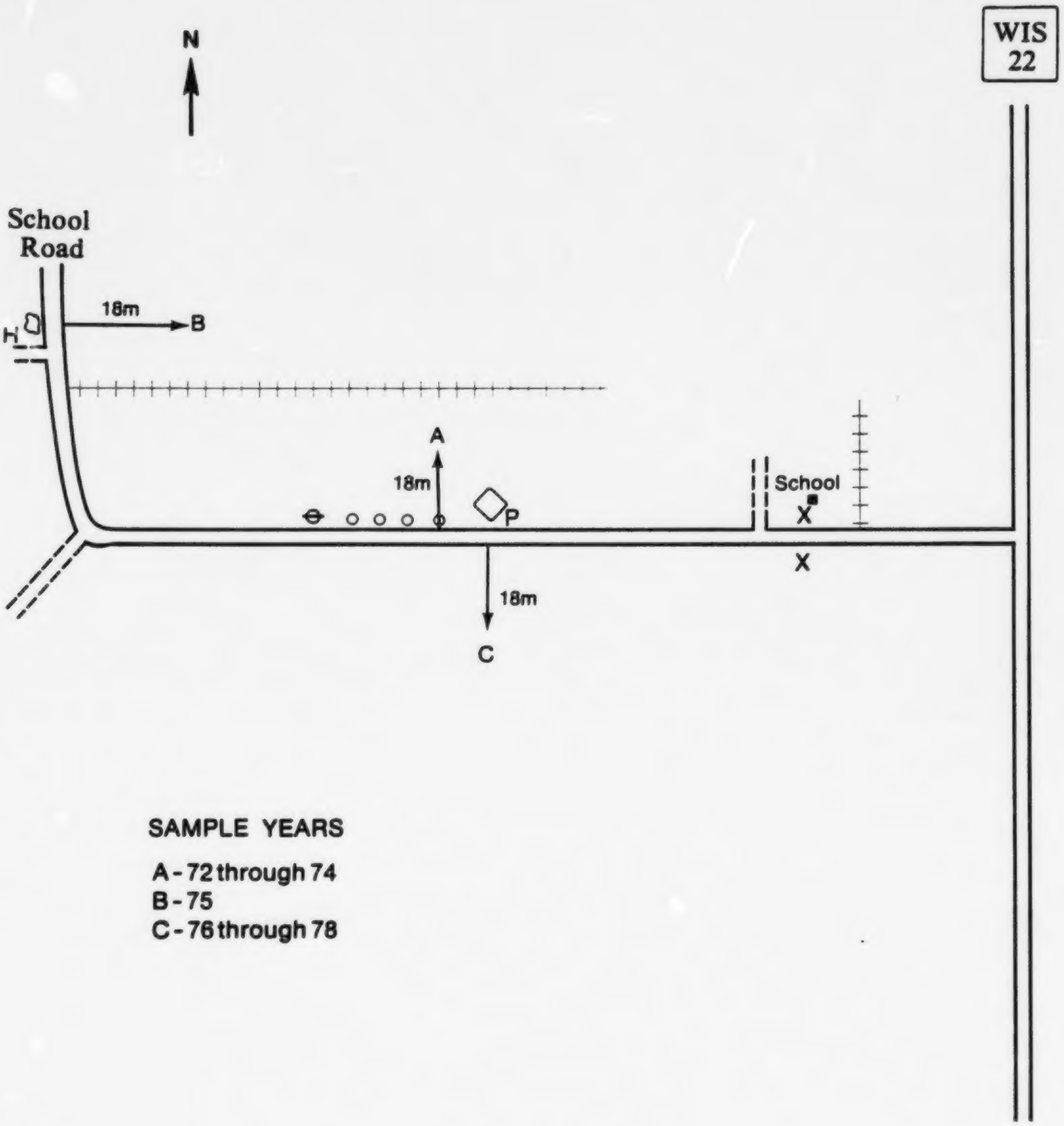
Site 7


P
N
A
18m
Mobile Homes
H
Warning Sign
C
18m
18m
B
H
Groth Road
Rush Road

SAMPLE YEARS

A - 72 through 75
B - 76
C - 77 and 78

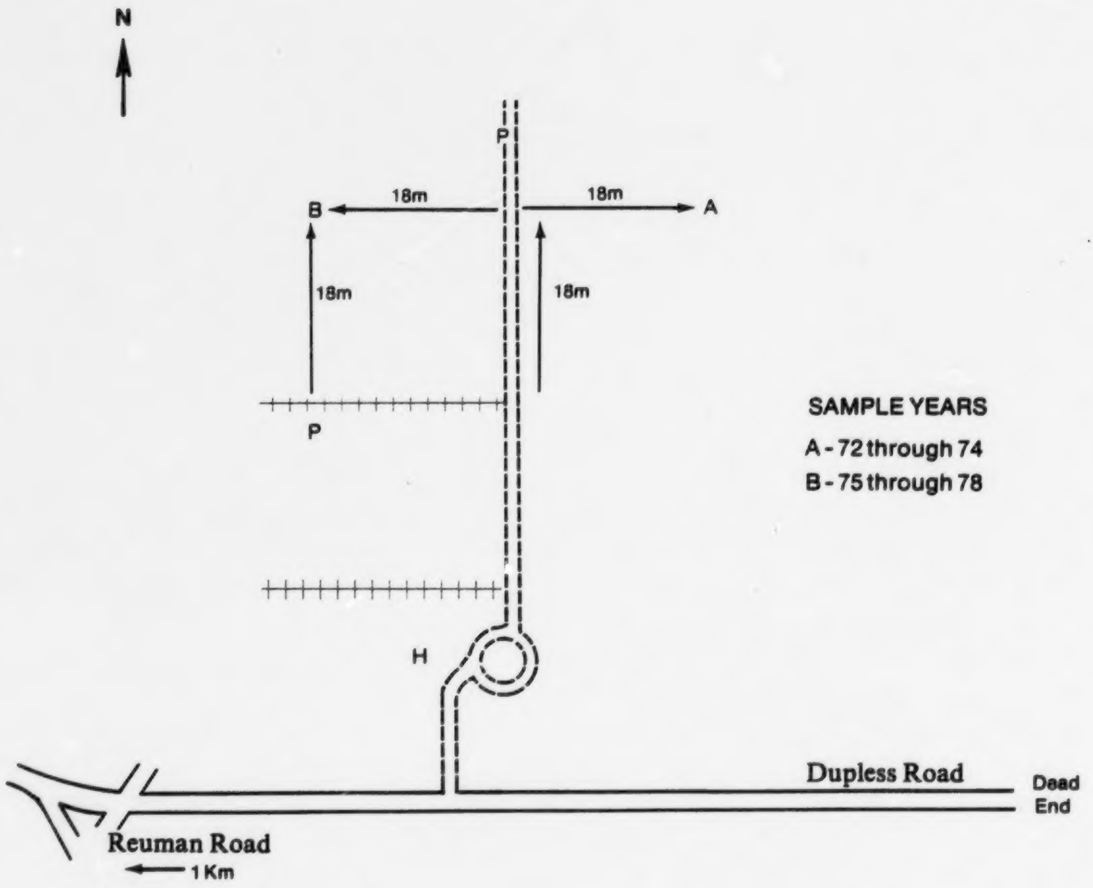
Site 8


N
School Road
WIS 22
H
18m
B
A
18m
P
School
X
X
18m
C

SAMPLE YEARS

A - 72 through 74
B - 75
C - 76 through 78

Site 9

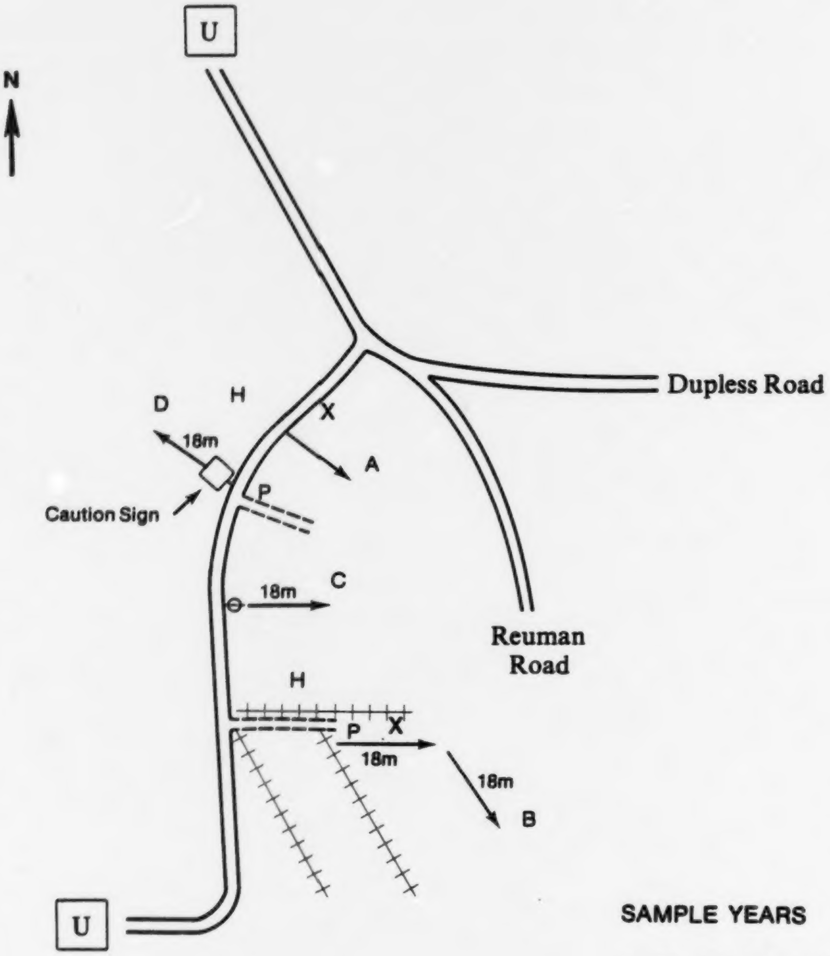

N
P
B
18m
18m
A
18m
18m
P
H
Dupless Road
Dead
End
Reuman Road
1 Km

SAMPLE YEARS

A - 72 through 74

B - 75 through 78

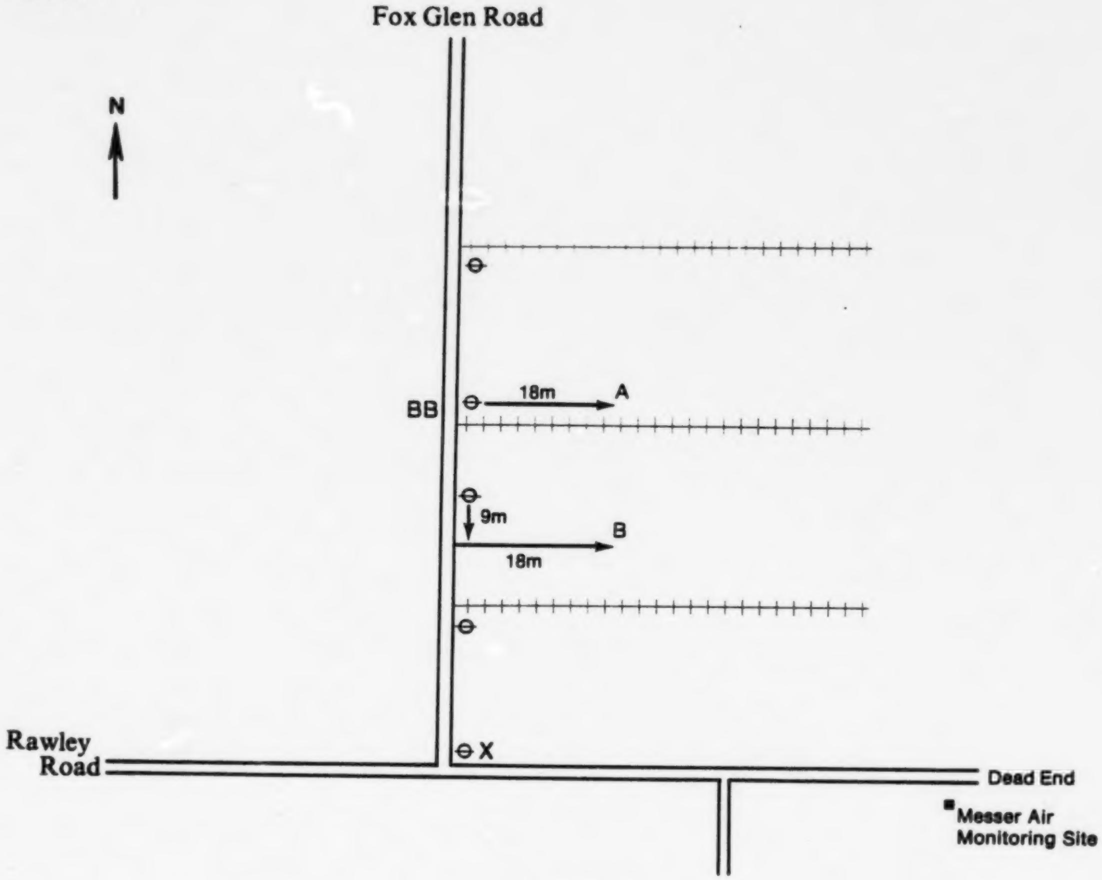
Site 10


U
N
Dupless Road
D
H
X
18m
A
Caution Sign
P
C
18m
Reuman Road
H
P
X
18m
18m
B
U

SAMPLE YEARS

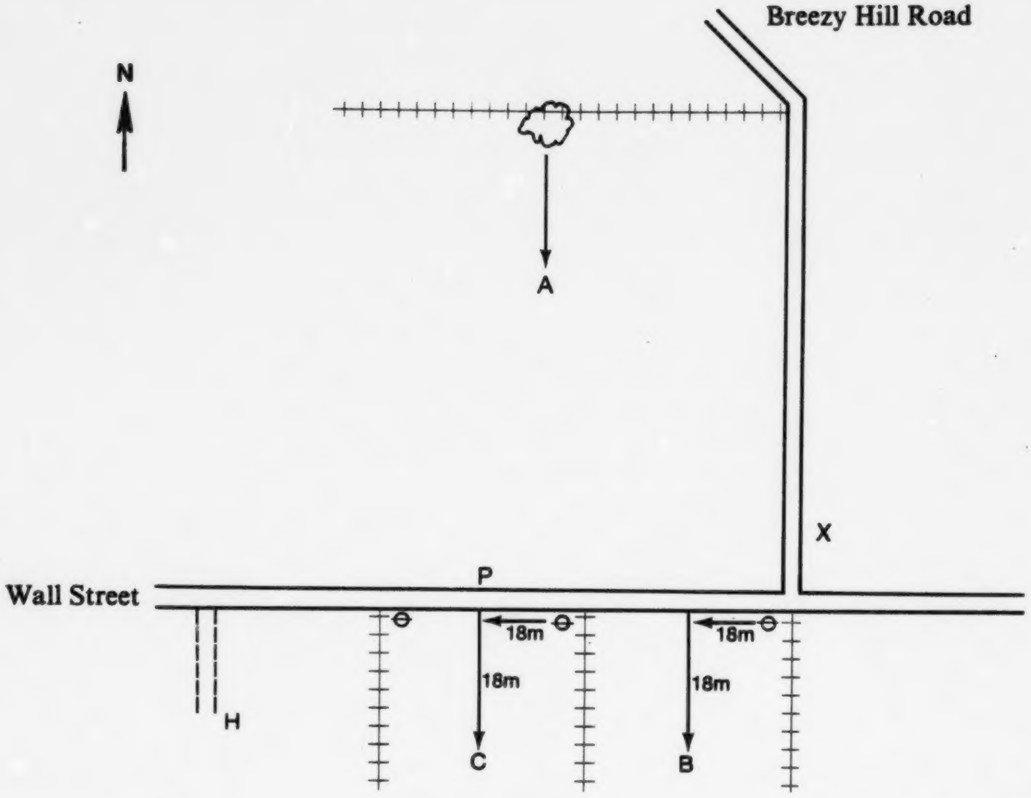
A - 72 (Exact location not recorded)
B - 73 and 74
C - 75
D - 76 through 78

Site 11


Fox Glen Road
N
18m
A
BB
9m
B
18m
X
Rawley Road
Dead End
Messer Air Monitoring Site

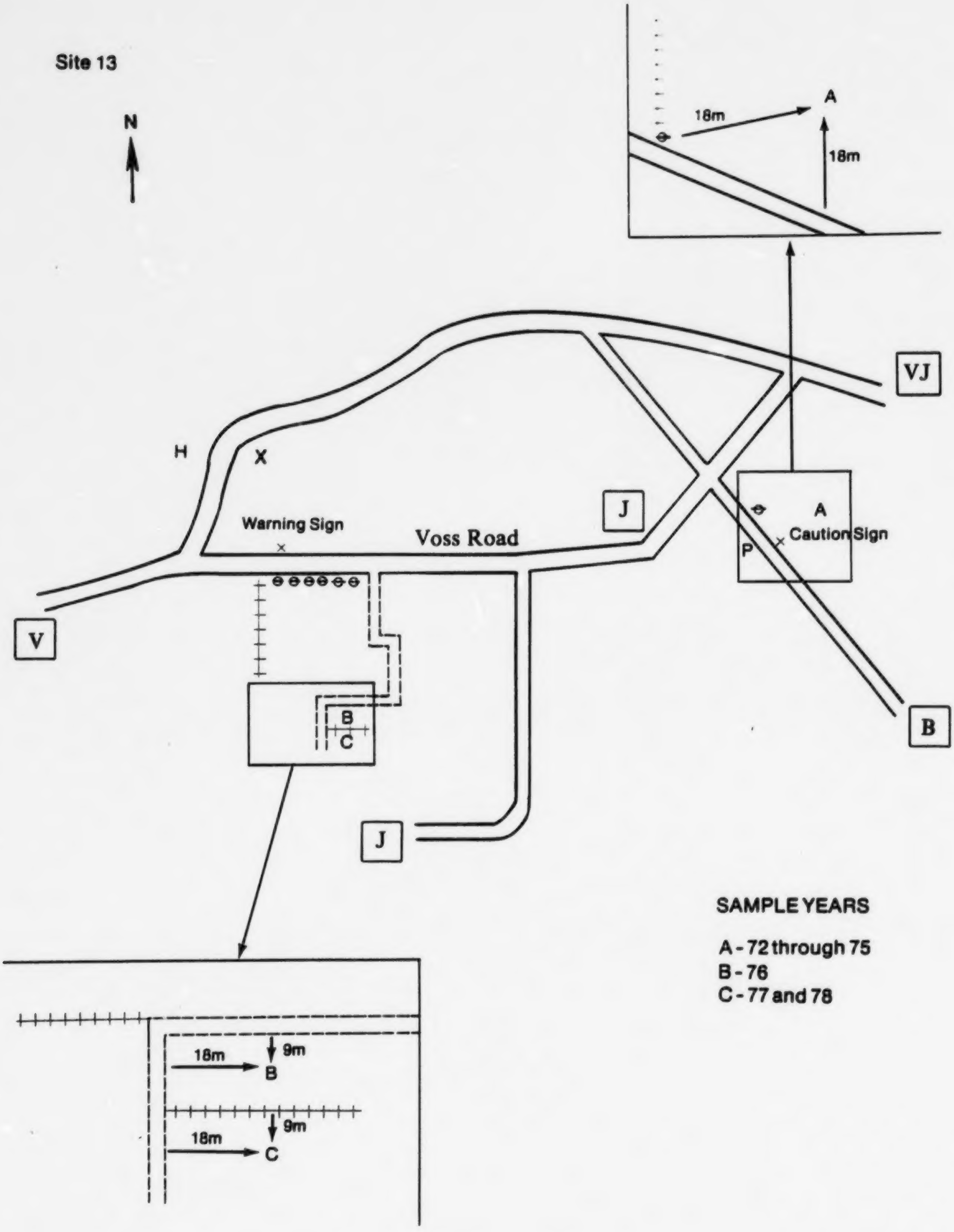
SAMPLE YEARS
A - 72 through 75, 78
B - 76 and 77

Site 12


N
Breezy Hill Road
A
X
P
Wall Street
18m
18m
18m
18m
H
C
B

SAMPLE YEARS
A-72 - Exact location not recorded
B-73 through 77
C-78

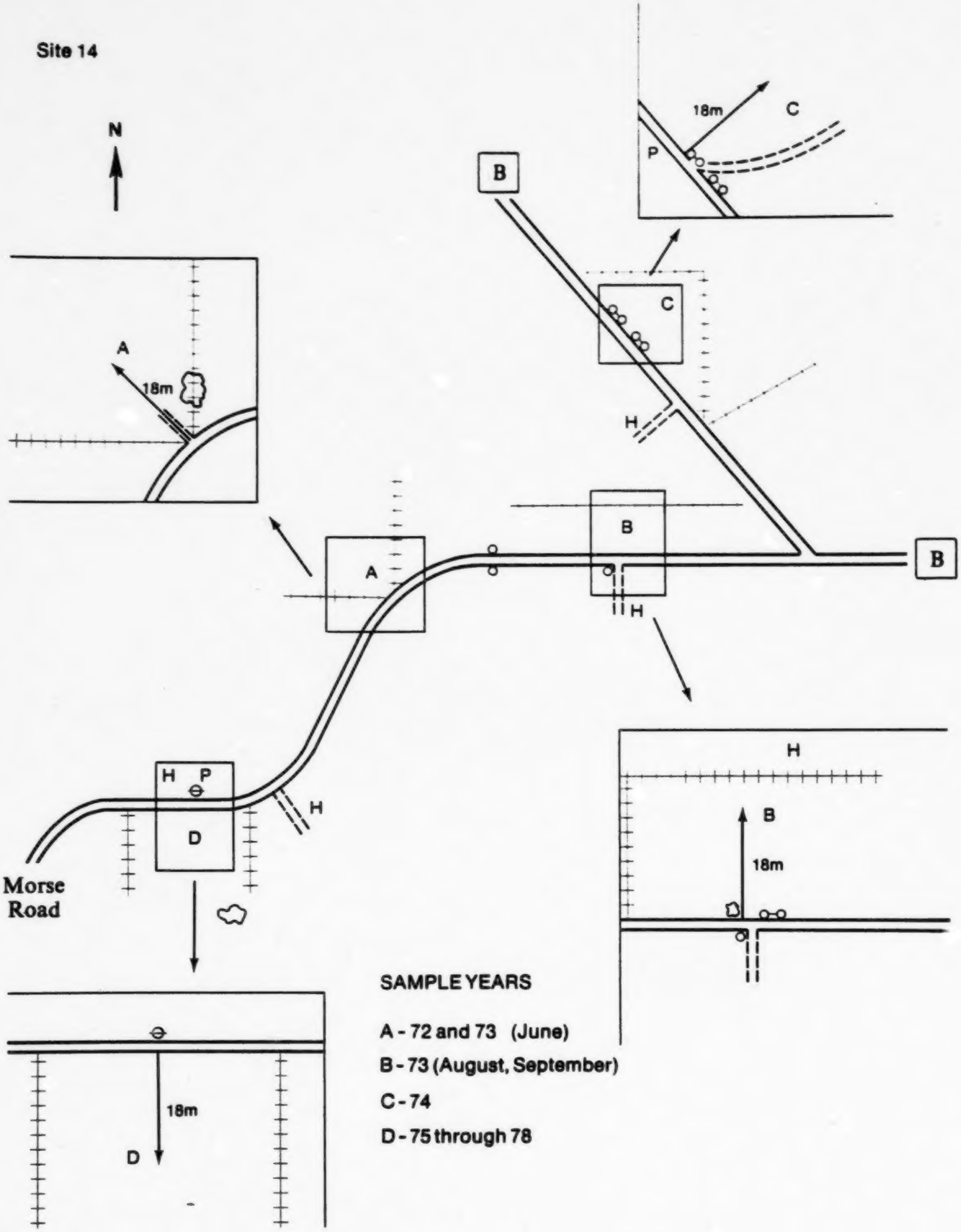
Site 13


N
18m
A
18m
VJ
H
X
J
Warning Sign
Voss Road
A
Caution Sign
P
V
B
C
B
J
18m
9m
B
9m
18m
C

SAMPLE YEARS

A - 72 through 75
B - 76
C - 77 and 78

Site 14


N
A
18m
B
C
P
H
A
B
H
H P
D
H
Morse Road
H
B
18m
18m
D

SAMPLE YEARS

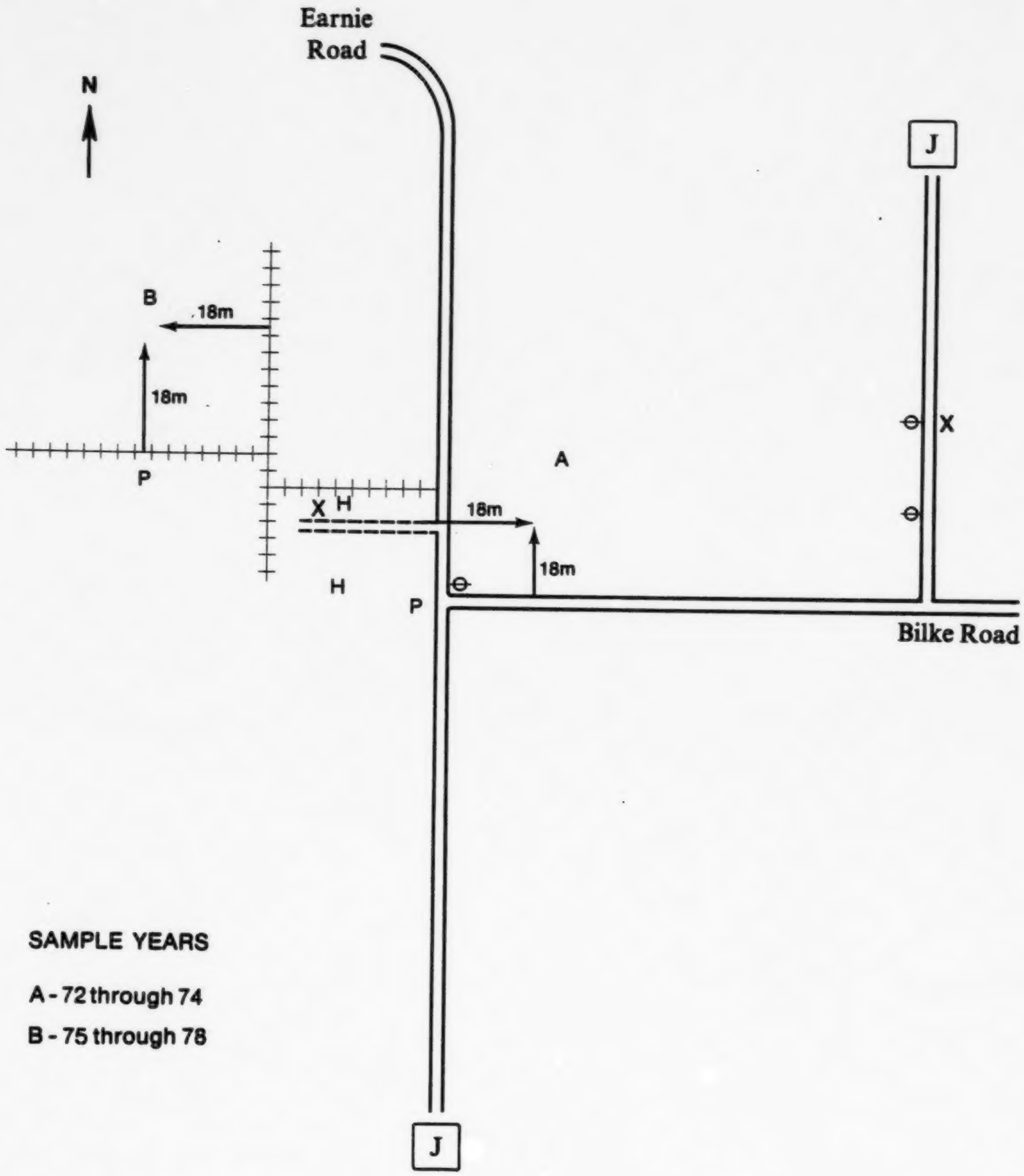
A - 72 and 73 (June)

B - 73 (August, September)

C - 74

D - 75 through 78

Site 15

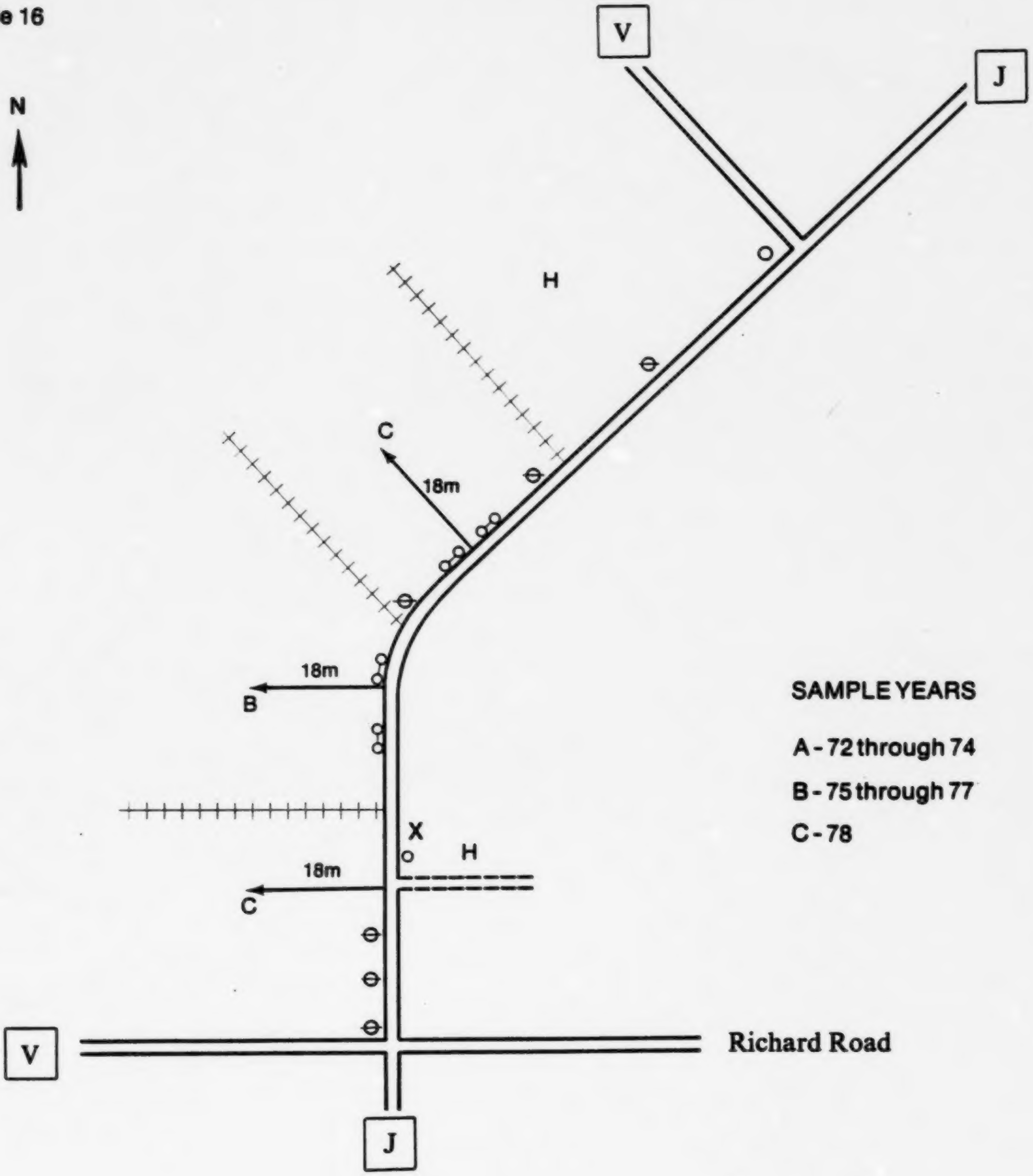

Earnie Road
N
B
18m
18m
P
A
X
X H
18m
18m
H
P
Bilke Road
J
J

SAMPLE YEARS

A - 72 through 74

B - 75 through 78

Site 16


V
J
N
H
C
18m
18m
B
X
H
18m
C
SAMPLE YEARS
A - 72 through 74
B - 75 through 77
C - 78
V
Richard Road
J